Declarative Networking

Abstract
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Declarative Networking

Boon Thau Loo and Wenchao Zhou, University of Pennsylvania

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Declarative Networking
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Boon Thau Loo and Wenchao Zhou
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KEYWORDS

declarative networking, datalog, recursive query processing
To Foo Lee Yoong
   (Boon Thau Loo’s mother)

   and

To Yiqing Ren
   (Wenchao Zhou’s wife)

February 2012.
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Boon Thau Loo and Wenchao Zhou
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CHAPTER 1

Introduction

Over the past decade, there has been intense interest in the design of new network protocols. This has been driven from below by an increasing diversity in network architectures (including wireless networks, satellite communications, and delay-tolerant rural networks) and from above by a quickly growing suite of networked applications (peer-to-peer systems, sensor networks, content distribution, etc.)

Network protocol design and implementation is a challenging process. This is not only because of the distributed nature and large scale of typical networks, but also because of the need to balance the extensibility and flexibility of these protocols on one hand, and their robustness and efficiency on the other hand. One need look no further than the Internet for an illustration of these hard tradeoffs. Today’s Internet routing protocols, while arguably robust and efficient, make it hard to accommodate the needs of new applications such as improved resilience and higher throughput. Upgrading even a single router is hard. Getting a distributed routing protocol implemented correctly is even harder. And, in order to change or upgrade a deployed routing protocol today, one must get access to each router to modify its software. This process is made even more tedious and error-prone by the use of conventional programming languages.

This book presents the design and implementation of declarative networking [Loo et al., 2005a,b, 2006, 2009], an application of database query-language and processing techniques to the domain of networking. Declarative networking is based on the observation that network protocols deal at their core with computing and maintaining distributed state (e.g., routes, sessions, performance statistics) according to basic information locally available at each node (e.g., neighbor tables, link measurements, local clocks) while enforcing constraints such as local routing policies. Recursive query languages studied in the deductive database literature [Ramakrishnan and Ullman, 1993] are a natural fit for expressing the relationship between base data, derived data, and the associated constraints. Simple extensions to these languages and their implementations enable the natural expression and efficient execution of network protocols.

The high-level goal of declarative networking is to provide software environments that can accelerate the process of specifying, implementing, experimenting with and evolving designs for network architectures. Declarative networking can reduce program sizes by orders of magnitude relative to traditional approaches, in some cases resulting in programs that are line-for-line translations of pseudocode in networking research papers. In addition to serving as a platform for rapid prototyping of network protocols, declarative networking also open up opportunities for automatic protocol optimization and hybridization, program checking and debugging.
2 1. INTRODUCTION

As evidence of its widespread applicability, declarative techniques have been used in several domains including fault tolerance protocols [Singh et al., 2008], cloud computing [Alvaro et al., 2010], sensor networks [Chu et al., 2007], overlay network compositions [Mao et al., 2008], anonymity systems [Sherr et al., 2010], mobile ad-hoc networks [Liu et al., 2011a, Muthukumar et al., 2009a], wireless channel selection [Liu et al., 2012], network configuration management [Chen et al., 2010], and as a basis for course projects in a distributed systems class [Gill et al., 2011] at the University of Pennsylvania. An open-source declarative networking platform called RapidNet [RapidNet] has also been integrated with the emerging ns-3 [ns-3] simulator, demonstrated at SIGCOMM’09 [Muthukumar et al., 2009b], and successfully deployed on testbeds such as PlanetLab [PlanetLab] and ORBIT [ORBIT].

1.1 OVERVIEW OF DECLARATIVE NETWORKS

Figure 1.1: A Declarative Network

Figure 1.1 illustrates a declarative network at a conceptual level. Like any traditional network, a declarative network maintains network state at each node to enable the routing and forwarding of packets. The network state is stored as relational tables distributed across the network, similar to a traditional distributed database [Özsu and Valduriez, 2011]. Network protocols are declaratively specified as distributed recursive queries over the network state. Recursive queries have traditionally been used in the database community for posing queries over graph structures in deductive databases. The main observation that inspired this work on declarative networking is that these recursive queries are a natural fit for expressing network protocols, which themselves are based on recursive relations among nodes in the network.

The recursive query language used in declarative networking is a distributed variant of Datalog called Network Datalog (NDlog). Intuitively, one can view the forwarding tables generated by network protocols as the output of distributed recursive queries over changing input network state (network
1.2. THE CASE FOR DECLARATIVE NETWORKING

Network protocols are specified as NDlog programs and disseminated in the network. Upon receiving NDlog programs, each node compiles the declarative specifications into execution plans in the form of distributed dataflows. When executed, these dataflows generate message exchanges among nodes as well as network state modifications, resulting in the implementation of the network protocols. Multiple declarative networks can run simultaneously, either as separate dataflows, or compiled into a single dataflow where common functionalities among the protocols can be shared.

1.2 THE CASE FOR DECLARATIVE NETWORKING

Declarative networking presents three advantages over existing approaches: ease of programming, optimizability and balance between extensibility and safety. We summarize the advantages in the rest of this section.

1.2.1 EASE OF PROGRAMMING

A declarative language allows us to specify at a high level “what” to do, rather than “how” to do it. When feasible, the declarative approach can lead to ease of programming and significant reduction in code size. As demonstrated in Chapter 5, NDlog can express a variety of well-known routing protocols (e.g., distance vector, path vector, dynamic source routing, link state, multicast) in a compact and clean fashion, typically in a handful of lines of program code. Moreover, higher-level routing concepts (e.g., QoS constraints) can be achieved via simple modifications to these programs. Furthermore, Chapter 6 shows that complex application-level overlay networks can also be expressed naturally in NDlog.

Declarative network descriptions can be extremely concise. For example, the Chord overlay network can be specified in 48 NDlog rules, versus thousands of lines of code for the MIT Chord reference implementation. Also, the high-level, declarative specifications means that they decompose cleanly into logically reusable units: for instance, for composing various overlay networks together [Mao et al., 2008]. Moreover, by providing a uniform declarative language for distributed querying and networking, we enable the natural integration of distributed information-gathering tasks like resource discovery and network status monitoring.

In addition to ease of programming, there are other advantages to the use of a high level language. For example, NDlog specifications can illustrate unexpected relations between network protocols, as we illustrate in Chapter 7. In particular, the path vector and dynamic source routing protocols differ only in a simple, traditional database optimization decision: the order in which a query's predicates are evaluated. The use of higher-level abstractions also provides the potential to statically check network protocols for security and correctness properties. Dynamic runtime checks to test distributed properties of the network can also be easily expressed as declarative queries, providing a uniform framework for network specification, monitoring and debugging.
1. INTRODUCTION

1.2.2 OPTIMIZABILITY

Declarative networking achieves performance comparable to traditional approaches. Moreover, by using a declarative framework rooted in databases, better performance can be achieved by utilizing query processing and optimization techniques that are well-studied in the database community.

The declarative approach to protocol specification reveals new opportunities for optimizing network protocols. First, the use of a high-level declarative language facilitates the identification and sharing of common functionalities among different declarative networks. Second, off-the-shelf database optimization techniques can be applied to declarative routing specifications to achieve tangible performance benefits. Third, new optimization techniques suited to the distributed, soft-state context of network protocols are developed.

1.2.3 BALANCE OF EXTENSIBILITY AND SAFETY

In addition to the benefits of having a higher-level, compact specification, declarative networking achieves a better balance between extensibility and safety compared to existing solutions. Extensibility, or the ability to easily add new functionality to existing systems, is an important requirement in our setting as a means of rapid deployment and experimentation with network protocols. However, extensibility has traditionally been achieved at the expense of security [Bershad et al., 1995, Stonebraker, 1986]. In the network domain, this concern is best illustrated by active networks [Tennenhouse et al., 1997] which, at the extreme, allow routers to download and execute arbitrary code. While active networks provide full generality, security concerns have limited their practical use.

Declarative networking can be viewed as a safer, restricted instantiation of active networks, where NDlog is proposed as a Domain Specific Language (DSL) for programming a network. The core of NDlog is Datalog, which has complexity polynomial in the size of the network state [Abiteboul et al., 1995]. While the language extensions to NDlog alter its theoretical worst-case complexity, there exist static analysis tests on termination for a large class of recursive queries [Krishnamurthy et al., 1996]. This addresses the safety aspect of security, where specified protocols can now be checked to ensure that they do not consume infinite resources before execution. In addition, by “sandboxing” NDlog programs within a database query engine, undesirable side-effects are contained during query execution. Safety analysis of declarative networking protocols will be discussed in Chapter 8.

1.3 ORGANIZATION

This book is organized as follows.

Chapter 2 provides an introduction to Datalog, and then motivates and formally defines the NDlog language. NDlog builds upon traditional Datalog to enable distributed and soft-state computations based on the underlying physical connectivity, all of which are essential in the network setting.
Chapter 3 describes the implementation of a declarative networking engine, and query processing techniques for compiling NDlog programs into execution plans. We further introduce two representative open-source declarative networking engines, P2 [P2] and its successor RapidNet [RapidNet].

Chapter 4 introduces relaxed versions of the traditional, centralized execution strategy known as semi-naïve [Balbin and Ramamohanarao, 1987] fixpoint evaluation. The pipelined semi-naïve evaluation technique overcome fundamental problems of semi-naïve evaluation in an asynchronous distributed setting. In the network setting, transactional isolation of updates from concurrent queries is often inappropriate; network protocols must incorporate concurrent updates about the state of the network while they run. This is addressed by formalizing the typical distributed systems notion of “eventual consistency” in declarative networking’s context of derived data. Using techniques from materialized recursive view maintenance, updates to input tables during NDlog program execution are incorporated, while ensuring well-defined eventual consistency semantics.

Chapter 5 demonstrates the expressiveness of NDlog in compactly specifying declarative routing protocols that implement a variety of well-known routing protocols. NDlog programs are a natural and compact way of expressing a variety of well-known routing protocols, typically in a handful of lines of program code. This allows ease of customization, where higher-level routing concepts (e.g., QoS constraints) can be achieved via simple modifications to the NDlog programs.

Chapter 6 further applies the declarative framework to more challenging scenarios, where NDlog is used to specify complex overlay networks such as the Narada mesh [Chu et al., 2000] for end-system multicast and the Chord distributed hash table. The declarative Chord implementation is roughly two orders of magnitude less code than the original C++ implementation.

Chapter 7 discusses and evaluates a number of query optimizations that arise in the declarative networking context. These include applications of traditional database techniques such as aggregate selections [Furfaro et al., 2002, Sudarshan and Ramakrishnan, 1991] and magic-sets rewriting [Bancilhon et al., 1986, Beeri and Ramakrishnan, 1987], as well as new optimizations we develop for work-sharing, caching, and cost-based optimizations based on graph statistics.

Chapter 8 describes recent advances in declarative networking, tracing its evolution from a rapid prototyping framework towards a platform that serves as an important bridge connecting formal theories for reasoning about protocol correctness and actual implementations. In particular, the chapter presents recent uses of declarative networking for addressing four main challenges in the distributed systems development cycle: the generation of safe routing implementations, debugging, security and privacy, and optimizing distributed systems.

Chapter 9 concludes by summarizing the overall impact of declarative networking.
CHAPTER 2

Declarative Networking Language

This chapter formally defines the Network Datalog (NDlog) language for declarative networking. The NDlog language is based on extensions to traditional Datalog, a well-known recursive query language designed and traditionally used for querying graph-structured data in a centralized database.

This chapter is organized as follows. Section 2.1 provides an introduction to Datalog. Section 2.2 presents the NDlog language using an example program that computes all-pairs shortest paths in a network from specification to execution. Based on this example program, NDlog extensions to traditional Datalog are highlighted. Furthermore, the connection to routing is established, by showing that the execution of this program resembles a well-known routing protocol for computing shortest paths in a network.

Following the example, in Sections 2.3, 2.4 and 2.5, we formally describe the data and query model of NDlog that addresses its four main requirements: distributed computation, soft-state data and rules, and incremental maintenance of network state.

2.1 INTRODUCTION TO DATALOG

Following the conventions in the Ramakrishnan and Ullman [1993] survey, a Datalog program consists of a set of declarative rules and an optional query. Since these programs are commonly called “recursive queries” in the database literature, the terms “query” and “program” are used interchangeably when referring to a Datalog program.

A Datalog rule has the form \( p : q_1, q_2, ..., q_n \), which can be read informally as “\( q_1 \) and \( q_2 \) and ... and \( q_n \) imply \( p \)”. The predicate \( p \) is the head of the rule, and \( q_1, q_2, ..., q_n \) is a list of literals that constitutes the body of the rule. Literals are either predicates over fields (variables and constants), or function symbols applied to fields. The rules can refer to each other in a cyclic fashion to express recursion. The order in which the rules are presented in a program is semantically immaterial. The commas separating the predicates in a rule are logical conjuncts (AND); the order in which predicates appear in a rule body also has no semantic significance, though most implementations (including declarative networking engines) employ a left-to-right execution strategy. The query specifies the output of interest.

The predicates in the body and head of traditional Datalog rules are relations, and they are interchangeably referred to in this book as predicates, relations or tables. The number and types of fields in relations are inferred from their (consistent) use in the program’s rules. Each relation has a
8 2. DECLARATIVE NETWORKING LANGUAGE

primary key, which consists of a set of fields that uniquely identify each tuple within the relation. In
the absence of other information, the primary key is taken to be the full set of fields in the relation.

By convention, the names of predicates, function symbols and constants begin with a lower-
case letter, while variable names begin with an upper-case letter. Most implementations of Datalog
enhance it with a limited set of function calls (which start with “f_” in NDlog’s syntax), including
boolean predicates and arithmetic computations. Aggregate constructs are represented as functions
with field variables within angle brackets (<>). Negated predicates are not used in declarative
networking.

As an example, Figure 2.1 shows a Datalog program that computes the next hop along the
shortest paths between all pairs of nodes in a graph. The program abbreviates some of its predicates
as shown in Figure 2.2. The program has four rules (which for convenience are labeled r1-r4), and
takes as input a base ("extensional") relation link(Source, Destination, Cost). Rules r1-r2
are used to derive “paths” in the graph, represented as tuples in the derived ("intensional") relation
path(S, D, Z, C). The S and D fields represent the source and destination endpoints of the path; Z
contains the “next hop” in the graph along the path that a node S should take in order to go to node
D; and C represents the cost of the path.

Rule r1 produces path tuples directly from existing link tuples, and rule r2 recursively
produces path tuples of increasing cost by matching (or unifying) the destination fields of existing
links to the source fields of previously computed paths. The matching is expressed using the repeated
“Z” variable in link(S, Z, C1) and path(Z, D, Z2, C2) of rule r2. Intuitively, rule r2 says that “if
there is a link from node S to node Z, and there is a path from node Z to node D, then there is a path
from node S to node D via Z”.

Given the path relation, rule r3 derives the relation spCost(S, D, C) that computes the
minimum cost C for each source (S) and destination (D) for all input paths. Rule r4 takes as input
spCost and path tuples and then computes shortestPathHop(S, D, Z, C) tuples that contains
the next hop (Z) along the shortest path from S to D with cost C. Last, the Query specifies the output
of interest to be the shortestPath table.

<table>
<thead>
<tr>
<th>Rule</th>
<th>Datalog Rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>r1</td>
<td>path(S, D, D, C) :- link(S, D, C).</td>
</tr>
<tr>
<td>r2</td>
<td>path(S, D, Z, C) :- link(S, Z, C1), path(Z, D, Z2, C2), C = C1 + C2.</td>
</tr>
<tr>
<td>r3</td>
<td>spCost(S, D, min &lt;C&gt;) :- path(S, D, Z, C).</td>
</tr>
<tr>
<td>r4</td>
<td>shortestPathHop(S, D, C) :- spCost(S, D, C), path(S, D, Z, C).</td>
</tr>
</tbody>
</table>

Query shortestPathHop(S, D, Z, C).

Figure 2.1: Shortest-Path-Hop Datalog program.

2.2 NETWORK DATALOG BY EXAMPLE

Before diving into the formal definitions of NDlog, Figure 2.3 shows an example using a distributed
variant of the earlier Shortest-Path-Hop Datalog program. This distributed NDlog program computes
2.2. NETWORK DATA LOG BY EXAMPLE

<table>
<thead>
<tr>
<th>Predicate</th>
<th>Schema</th>
</tr>
</thead>
<tbody>
<tr>
<td>link(S,D,C)</td>
<td>path(Source, Destination, Cost)</td>
</tr>
<tr>
<td>path(S,D,Z,C)</td>
<td>path(Source, Destination, NextHop, Cost)</td>
</tr>
<tr>
<td>spCost(S,D,C)</td>
<td>spCost(Source, Destination, Cost)</td>
</tr>
<tr>
<td>shortestPathHop(S,D,Z,C)</td>
<td>shortestPathHop(Source, Destination, NextHop, Cost)</td>
</tr>
</tbody>
</table>

Figure 2.2: Predicates and the corresponding schemas used in the Shortest-Path-Hop Datalog program shown in Figure 2.1.

materialize(link,infinity,infinity,keys(1,2)).
materialize(path,infinity,infinity,keys(1,2,3,4)).
materialize(spCost,infinity,infinity,keys(1,2)).
materialize(shortestPathHop,infinity,infinity,keys(1,2)).
sh1 path(@S,D,D,C) :- link(@S,D,C).
sh2 path(@S,D,Z,C) :- link(@S,Z,C1), path(@Z,D,Z2,C2), C = C1 + C2.
sh3 spCost(@S,D,min< <C>) :- path(@S,D,Z,C).
sh4 shortestPathHop(@S,D,Z,C) :- spCost(@S,D,C), path(@S,D,Z,C).
Query shortestPathHop(@S,D,Z,C).

Figure 2.3: Shortest-Path-Hop NDlog program.

for every node, the next hop along the shortest paths of all nodes in a network in a distributed fashion. This NDlog program is used to highlight the following key points:

- NDlog builds upon traditional Datalog in order to meet three new requirements: distributed computation, soft-state data and rules, and incremental maintenance of network state.

- When this program is executed, the resulting communication and network state resembles the well-known distance vector and path vector routing protocols [Peterson and Davie, 2007].

- This example program demonstrates the compactness of NDlog. In four NDlog rules, one can specify and implement a routing protocol widely used to compute shortest routes in a network.

2.2.1 OVERVIEW OF NDLOG

An NDlog program is largely composed of table declaration statements and rules. In NDlog, all input relations and rule derivations are stored in materialized tables. Unlike Datalog, tables must be defined explicitly in NDlog via materialize statements, which specify constraints on the size and lifetime of tuple storage—any relations not declared as tables are treated as named streams of tuples. Each materialize(name, lifetime, size, primary keys) statement specifies the relation name, lifetime of each tuple in the relation, maximum size of the relation, and fields making up the
primary key of each relation. If the primary key is the empty set \( \emptyset \), then the primary key is the full set of fields in the relation. For example, in the Shortest-Path-Hop NDlog program, all the tables are specified with infinite sizes and lifetimes.

The execution of NDlog rules will result in the derivation of tuples that are stored in materialized tables. For the duration of program execution, these materialized results are incrementally recomputed as the input relations are updated. For example, the update of link tuples will result in new derivations and updates to existing path, spCost and shortestPathHop tuples. In addition, if an NDlog rule head is prepended with an optional keyword delete, the derived tuples are used to delete an exact match tuple in its relation instead.

Since network protocols are typically computations over distributed network state, one of the important requirements of NDlog is the ability to support rules that express distributed computations. NDlog builds upon traditional Datalog by providing control over the storage location of tuples explicitly in the syntax via location specifiers. Each location specifier is an attribute within a predicate that indicates the partitioning field of each relation. To illustrate, in Figure 2.3, each predicate in the NDlog rules has an “@” symbol prepended to a single field denoting the location specifier. For example, all path and link tuples are stored based on the address stored in the first field @S.

Interestingly, while NDlog is a language to describe networks, there are no explicit communication primitives. All communication is implicitly generated during rule execution as a result of data placement. For example, in rule sh2, the path and link predicates have different location specifiers, and in order to execute the rule body of sh2 based on their matching fields, link and path tuples have to be shipped in the network. It is the movement of these tuples that will generate the messages for the resulting network protocol.

### 2.2.2 FROM QUERY SPECIFICATIONS TO PROTOCOL EXECUTION

Having provided a high-level overview of NDlog, the execution of the Shortest-Path-Hop NDlog program is demonstrated via an example network shown in Figure 2.4. The resulting communication and network state generated in program execution resembles the distance-vector protocol [Peterson and Davie, 2007] that is commonly used to compute shortest paths in a network.

In the example network, each node is running the Shortest-Path-Hop program. For simplicity, only the derived paths along the solid lines are shown, even though the network connectivity is bidirectional (dashed lines). The discussion is necessarily informal since distributed implementation strategies have not yet been presented. Chapter 4 shows in greater detail the steps required to generate the execution plan. Here, the focus is on providing a high-level understanding of the data movement in the network during query processing.

In this example, communication is simplified and described in iterations, where at each iteration, each network node generates paths of increasing hop count, and then propagates these paths to neighbor nodes along links. Each path tuple contains the nextHop field, which indicates for

---

1 The convention used in declarative networking starts the offset by 1 in the declarative networking system, as 0 is reserved in the implementation for the table name.
Figure 2.4: Shortest-Path program example execution. 1 and p are used as abbreviations for link and path respectively.

each path the next hop to route the message in the network. In Figure 2.4, we show newly derived path tuples at each iteration. In the first iteration, all nodes initialize their local path tables to 1-hop path tuples using rule sh1. In the 2nd iteration, using rule sh2, each node takes the input path tuples generated in the previous iteration, and computes 2-hop paths, which are then propagated to its neighbors. For example, path(@a,d,b,6) is generated at node b using path(@b,d,d,1) from the second iteration, and propagated to node a.

As path tuples are being computed and received at nodes, spCost and shortestPathHop tuples are also incrementally computed. For example, node a computes path(@a,b,b,5) using rule sh1, and then derives spCost(@a,b,5) and shortestPathHop(@a,b,b,5) using rules sh4-sh5. In the next iteration, node a receives path(@a,b,c,2) from node c which has lower cost compared to the previous shortest cost of 5, and hence the new tuples spCost(@a,b,2) and shortestPathHop(@a,b,c,2) replaces the previous values.

In the presence of path cycles, the Shortest-Path-Hop program never terminates, as rules sp1 and sp2 will generate paths of ever increasing costs. However, this can be fixed by storing the entire path and adding a check for cycles within the rules. Alternatively, a well-known optimization (Section 7.1.1) can be used when costs are positive to avoid cycles. Intuitively, this optimization reduces communication overhead by sending only the path tuples that result in changes to the local spCost and shortestPathHop tables, hence limiting communication to only path tuples that contribute to the eventual shortest paths.

Interestingly, the computation of the above program resembles the computation of the distance vector protocol. In the distance vector protocol, each node advertises <destination, path-cost> information to all neighbors, which is similar to the path tuples exchanged by
nodes at each iteration. All nodes use these advertisements to update their routing tables with
the next hop along the shortest paths for each given destination. This is similar to computing new
shortestPathHop tuples from path tuples using rules sh3—sh4. The main difference between the
NDlog program and the actual distance vector computation is that rather than sending individual
path tuples between neighbors, the traditional distance vector method batches together a vector of
costs for all neighbors. In the Shortest-Path-Hop program, the protocol only propagates the nextHop and not
the entire path. In most practical network protocols such as the Border Gateway Protocol (BGP) [Peterson and Davie, 2007], the entire path is included either for source routing or more
commonly, to prevent infinite path cycles. This is typically known as the path vector protocol, where
the path vector is the list of nodes from the source to the destination.

Figure 2.5 shows the Shortest-Path NDlog program that implements the path-vector protocol.
The program is written with only minor modifications to the earlier Shortest-Path-Hop NDlog program. The program computes the entire path for a given source to destination, by adding an extra field in the path predicate that maintains the full path. The function f_init(X, Y) initializes the
path with nodes X and Y, and the function f_concatPath(N, P) prepends a node N to an existing
path P. Chapter 5 presents more examples of routing protocols.
2.2.3 OTHER REQUIREMENTS OF NDLOG

In addition to distributed computations, NDlog requires the following additional features for soft-state data and rules and incremental maintenance of network state. These features are briefly described here, followed by more detailed descriptions in the rest of the book.

- **Soft-state data and rules**: In typical network protocols, the generated network state is maintained as soft-state [Clark, 1988] data. In the soft-state storage model, stored data have a lifetime or time-to-live (TTL), and are deleted when the lifetime has expired. The soft-state storage model requires periodic communication to refresh network state. Soft-state is often favored in networking implementations because in a very simple manner it provides well-defined eventual consistency semantics. Intuitively, periodic refreshes to network state ensure that the eventual values are obtained even if there are transient errors such as reordered messages, node disconnection or link failures. While soft-state is useful for maintaining distributed state, declarative networking also makes extensive use of traditional “hard-state” data with infinite lifetimes for storing persistent counters, local machine state and archival logs.

- **Incremental maintenance of network state**: In practice, most network protocols are executed over a long period of time, and the protocol incrementally updates and repairs routing tables as the underlying network changes (link failures, node departures, etc). To better map into practical networking scenarios, one key distinction that differentiates the execution of NDlog from earlier work in Datalog is the support for continuous rule execution and results materialization, where all tuples derived from NDlog rules are materialized and incrementally updated as the underlying network changes. As in network protocols, such incremental maintenance is required both for timely updates and for avoiding the overhead of recomputing all routing tables “from scratch” whenever there are changes to the underlying network.

In the rest of this chapter, using the Shortest-Path program in Figure 2.5 as the primary example, the extensions to both the data and query model of traditional Datalog in order to handle the requirements of distributed computations (Section 2.3) are presented, namely: soft-state data and rules (Section 2.4), and incremental maintenance of network state (Section 2.5).

2.3 DISTRIBUTED COMPUTATION

From a database perspective, one novelty of declarative networking’s setting is that data are distributed and relations may be partitioned across sites. NDlog gives the program writer explicit control of data placement with the use of location specifiers in each predicate.

**Definition 2.1** A location specifier is a field in a predicate whose value per tuple indicates the network storage location of that tuple.

The location specifier field is of type address, having a value that represents a network location. It is used as a partitioning field for its table across all nodes in the network, similar to horizontally
partitioned tables in distributed databases [Özsu and Valduriez, 2011]. We require that each predicate has a single location specifier field that is notated by an “@” symbol. For example, the location specifier of \texttt{link(}@S,D,C\texttt{)} is \texttt{@S}. This means that all \texttt{link} tuples are stored based on the address value of the \texttt{@S} field.

Given that predicates have location specifiers, \textit{local} and \textit{distributed} rules can now be distinguished as follows.

**Definition 2.2** Local rules are rules that have the same location specifier in each predicate, including the head.

Non-local rules are otherwise known as \textit{distributed rules}. Local rules can be executed without any distributed logic. In the \textit{Shortest-Path} program, rules \texttt{sp1}, \texttt{sp3} and \texttt{sp4} are local, while \texttt{sp2} is a distributed rule since the \texttt{link} and \texttt{path} body predicates are stored at different locations.

### 2.4 SOFT-STATE DATA AND RULES

Types of relations and rules are distinguished based on hard-state and soft-state storage models. In the rest of this section, the \textit{Ping-Pong} program in Figure 2.6 is used to illustrate NDlog rules that manipulate soft-state data. Figure 2.7 presents the schemas and meanings of the predicates.

| materialize(link,10,infinity,keys(1,2)). |
| materialize(pingRTT,10,5,keys(1,2)). |
| materialize(pendingPing,10,5,keys(1,2)). |
| pp1 ping(@S,D,E) :- periodic(@S,E,5), link(@S,D). |
| pp2 pingMsg(S,@D,E) :- ping(@S,D,E), link(@S,D). |
| pp3 pendingPing(@S,D,E,T) :- ping(@S,D,E), T = f_now(). |
| pp4 pongMsg(@S,E) :- pingMsg(S,@D,E), link(@D,S). |
| pp5 pingRTT(@S,D,RTT) :- pongMsg(@S,E), pendingPing(@S,D,E,T), RTT = f_now() - T. |
| pp6 link(@S,D) :- pingRTT(@S,D,RTT). |

**Query** pingRTT(@S,D,RTT).

**Figure 2.6:** Ping-Pong NDlog program.

The \textit{Ping-Pong} program implements a simple ping program where each node periodically pings its neighbor nodes to compute the round-trip time (RTT). Unlike the earlier \textit{Shortest-Path} program, all relations used in the \textit{Ping-Pong} program are declared with finite lifetimes and sizes. There are also some relations such as \texttt{ping}, \texttt{pingMsg} and \texttt{pongMsg} that are not declared using the \texttt{materialize} keyword. These relations are known as \textit{event relations}, and they consist of zero-lifetime tuples that are used to execute rules but are not stored.
Rule pp1 is triggered periodically using the special periodic predicate. The periodic(\$S, E, 5) predicate denotes an infinite stream of periodic event tuples generated at node \$S every five seconds with random identifier E. This allows rule pp1 to generate at five second intervals, a ping(\$S, D, E) event tuple at source node \$S to all its neighbors with destination D. Each ping is uniquely identified with an event identifier E. Each ping tuple is then used to generate a pingMsg(S, @D, E) tuple that is sent to destination node D (rule pp2). A pendingPing(@S, D, E, T) tuple is also stored locally to record the creation time T of ping(\$S, D, E).

In rule pp4, whenever a node D receives a pingMsg(S, @D, E) tuple from the source node \$S, it replies with a pongMsg(@S, E) tuple to node \$S. Upon receiving the pingMsg(@S, E) tuple, rule pp5 is used by node \$S to compute the RTT between itself and node D based on the time recorded in pendingPing(@S, D, E, T). A successful reply to a ping message indicates that the neighbor is alive. This results in the refresh of link tuples in rule pp6.

### 2.4.1 HARD-STATE VS. SOFT-STATE DATA

NDlog distinguishes between hard-state and soft-state relations based on the lifetime parameter in materialized statements.

**Definition 2.3**  
A hard-state relation is one that is materialized with infinite lifetime.

Hard-state relations are similar to data stored in traditional databases, which are non-expiring and have to be deleted explicitly. The link relation in the Shortest-Path program is an example of a hard-state relation. All link tuples persist unless explicitly deleted. For derivations such as path in the Shortest-Path-Hop program, there can be multiple derivations for the same tuple. Hence, one needs to keep track of all such derivations for hard-state relations unless all derivations are invalidated due to deletions.

**Definition 2.4**  
A soft-state relation is one that is materialized with finite lifetime.

Tuples that are inserted into soft-state tables are stored only for the duration of the table’s lifetime. If required by the network protocol, these soft-state tuples can be refreshed via NDlog rules.
Unlike hard-state relations, there is no need to keep track of multiple derivations of the same tuple. Instead, a refresh occurs when the same tuple is inserted into the table, resulting in the extension of the tuple by its specified lifetime. For example, the link relation in the Ping-Pong program is a soft-state relation, and all link tuples generated are deleted after ten seconds unless they are refreshed by rule pp6 before they expire.

**Definition 2.5** An event relation is a soft-state relation with zero lifetime.

Event relations can either be declared explicitly via materialize statements with the lifetime parameter set to 0, or implicitly if they are not declared in any materialize statements. Event relations are typically used to represent message “streams” (e.g., pingMsg, pongMsg in the Ping-Pong program), or periodically generated local events via a built-in periodic predicate (e.g., in rule pp1):

**Definition 2.6** The periodic(@N,E,T,K) event relation is a built-in relation that represents a stream of event tuples generated at node N every T seconds (up to an optional K times) with a random event identifier E. If K is omitted, the stream is generated infinitely.

Built-in streams in NDLog are akin to the foreign functions of LDL++ [Arni et al., 2003] or the table functions of SQL, but their storage semantics are those of events, as described above. For example, the periodic(@S,E,5) in rule pp1 denotes an infinite stream of periodic event tuples generated at node S every 5 seconds with random identifier E.

### 2.4.2 HARD-STATE AND SOFT-STATE RULES

Following the definitions of hard-state and soft-state data, this section presents hard-state rules and soft-state rules, which differ on their use of hard-state and soft-state relations in the rules:

**Definition 2.7** A hard-state rule contains only hard-state predicates in the rule head and body.

**Definition 2.8** A soft-state rule contains at least one soft-state predicate in the rule head or body.

Soft-state rules are further classified as follows.

**Definition 2.9** A pure soft-state rule has a soft-state predicate in the rule head, and at least one soft-state predicate in the rule body.

**Definition 2.10** A derived soft-state rule has a soft-state predicate in the rule head, but only hard-state predicates in the rule body.
2.5. INCREMENTAL MAINTENANCE OF NETWORK STATE

Definition 2.11 An archival soft-state rule has a hard-state rule head, and at least one soft-state predicate in the rule body.

Archival soft-state rules are primarily used for archival or logging purposes. These rules derive hard-state tuples that persist even after the input soft-state tuples that generate them have expired.

Since event relations are considered soft-state relations (with zero lifetimes), they can be used in any of the three soft-state rules above. During rule execution, input event tuples persist long enough for rule execution to complete and are then discarded. Since they are not stored, NDlog does not model the possibility of two instantaneous events occurring simultaneously. Syntactically, this possibility is prevented by allowing no more than one event predicate in soft-state rule bodies.

Definition 2.12 An event soft-state rule is a soft-state rule with exactly one event predicate in the rule body.

Using the Ping-Pong program as example, all rules are pure soft-state relations since no hard-state relations are used in this program. In addition, rules pp1-pp5 are event soft-state rules that take as input one event predicate (periodic, ping, ping, pingMsg and pongMsg respectively).

2.5 INCREMENTAL MAINTENANCE OF NETWORK STATE

As in network protocols, NDlog rules are designed to be executed over a period of time and incrementally updated based on changes in the underlying network. During rule execution, depending on their specified lifetimes, all derived tuples are either stored in materialized table or generated as events. All materialized derivations have to be incrementally recomputed by long-running NDlog rules in order to maintain consistency with changes in the input base tables.

For hard-state rules, this involves the straightforward application of traditional materialized view maintenance techniques [Gupta et al., 1993]. Consider three types of modifications to hard-state relations: insertions of new tuples, deletions of existing tuples, and updates (which can be modeled as deletion followed by an insertion). Note that inserting a tuple where there is another tuple with the same primary key is considered an update, where the existing tuple is deleted before the new one is inserted.

As with traditional database materialized views, the deletions of any input relations result in cascaded deletions, which leads to the deletion of previously derived tuples. For example, whenever a link tuple is deleted, all path tuples that are generated using this link tuple have to be deleted as well. Since there can be multiple derivations of each unique tuple, one needs to keep track of all of them and only delete a tuple when all its derivations are deleted.

The incremental maintenance of soft-state rules is carried out in a slightly different fashion due to the presence of soft-state relations. Two types of modifications are considered: insertions of new tuples or refreshes of existing soft-state tuples. Recall from Section 2.4.1 that a refresh occurs when the same tuple is inserted into the table, resulting in the extension of the tuple by its specified
2. DECLARATIVE NETWORKING LANGUAGE

Lifetime. These soft-state refreshes in turn lead to cascaded refreshes, where previously derived soft-state tuples are rederived and hence also refreshed. Unlike the maintenance of hard-state rules, cascaded deletions do not occur in soft-state rules. Instead, all derived soft-state tuples are stored for their specified lifetimes and timeout in a manner consistent with traditional soft-state semantics.

2.6 SUMMARY OF NETWORK DATALOG

Given the above preliminaries, the NDlog data model is based on the relational model with the following constraints.

1. All NDlog relations are horizontally partitioned in the network based on the location specifier attribute.
2. An NDlog relation is either a hard-state or soft-state relation depending on its lifetime.

An NDlog program is a Datalog program that satisfies the following syntactic constraints.

1. All predicates in an NDlog rule head or rule body have a location specifier attribute.
2. An NDlog rule is either a hard-state or soft-state rule.

In addition, the results of executing NDlog rules are materialized for their table lifetimes, and incrementally maintained as described in Section 2.5.

Interestingly, NDlog uses a somewhat more physical data model than the relational model, and a correspondingly somewhat more physical language. The main reason for doing this is to capture the essence of a network protocol—communication over links—in a way that remains largely declarative, leaving significant latitude for a compiler to choose an implementation of the specification. Note that most aspects of a program other than storage location and communication pairs are left unspecified—this includes the order in which tuples of a set are handled and the order in which predicates of a rule are considered. In addition, the need for partitioning via location specifiers reflects low-level networks. In principle, given a network implemented in this manner to achieve all-pairs communication, higher-level logic could be written without reference to locations or links. This is a natural extension to NDlog, and has since been explored in subsequent language extensions [Mao et al., 2008, Marczak et al., 2010].

2.7 SUMMARY

This chapter formally defined the NDlog language. The NDlog language is based on Datalog, and includes extensions to address NDlog’s three main requirements of distributed computation, support for soft-state data and rules, and incremental maintenance of network state. All of these extensions have been motivated by the distributed settings targeted in declarative networking, which are a departure from the environments in which traditional Datalog was used. The subsequent chapters then present two concrete instances of declarative networking, namely declarative routing and declarative overlays,
and describe in detail how NDlog programs are processed and executed to implement the network protocols.
CHAPTER 3

Declarative Networking
Overview

Having presented a variety of declarative routing protocols using NDlog, the next two chapters describe how NDlog programs can be compiled and executed to implement the network protocols. This chapter in particular is primarily focused on providing an overview of a declarative networking (DN) engine implementation, largely drawn from the experiences of the P2 system [P2]. The next chapter will focus specifically on the system component that processes NDlog programs.

The chapter is organized as follows. Section 3.1 presents the architectural overview of a DN engine and its different components. Section 3.2 describes the runtime engine used by declarative networking. Section 3.3 shows how network state is stored and managed as tables. The chapter concludes in Section 3.3.1 with a description of RapidNet, a recent successor of the P2 system.

3.1 ARCHITECTURE

Figure 3.1 shows the architecture of a declarative networking system from the perspective of a single node. There are three main components: the planner, dataflow installer, and dataflow engine. The DN engine utilizes a dataflow framework at runtime for maintaining network state. DN dataflows are similar to database query plans, which consist of graphs that connect various database “operators” with dataflow edges that represent the passing of tuples among operators, possibly across a network.

To implement a network protocol, the planner takes as input the network specification expressed as a NDlog program, and compiles the program into a dataflow graph. In order to disseminate NDlog programs throughout a network, a DN runtime system provides simple mechanisms for each node to send input NDlog programs by flooding its neighbors. When a dataflow is installed (i.e., the planner has created and inter-connected the database operators according to the compiled dataflow), all the required local tables and indices necessary for the program are also created. Indices are created for every table’s primary key, and additional indices are constructed on any table columns that are involved in unification (relational join). Once installed, dataflows are executed by the runtime engine until they are explicitly canceled.

The execution of the dataflow graph results in the implementation of the network protocol itself. The dataflow graph is registered locally at each node’s dataflow engine via a dataflow installer. Each local dataflow participates in a global, distributed dataflow, with messages flowing among dataflows executed at different nodes, resulting in updates to the network state used by the network protocol. The distributed dataflow when executed performs the operations of a network protocol.
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The local tables store the state of the network protocols, and the flow of messages entering and leaving the dataflow constitute the network messages generated by the executing protocol.

3.2 DN DATAFLOW ENGINE

Figure 3.1: Components of a single declarative networking node.

Figure 3.2: Dataflow example at a single node.
The dataflow engine of DN was inspired by prior work in both databases and networking. Software dataflow architectures occupy a constrained but surprisingly rich design space that has been explored in a variety of contexts. Dataflow graphs have been used previously by parallel and distributed database query systems like Gamma [DeWitt et al., 1986], Volcano [Graefe, 1990] and PIER [Huebsch et al., 2005] as their basic query executables.

The use of the dataflow framework has recently been explored in related work on extensible networks. For example, software router toolkits like Scout [Mosberger and Peterson, 1996], Click [Kohler et al., 2000] and XORP [Handley et al., 2005] in recent years have demonstrated that network message handling and protocol implementation can be neatly factored into dataflow diagrams. This book adopts the Click term *element* for a node in a DN dataflow graph, but as in database query plans, each edge in the graph carries a stream of well structured tuples, rather than annotated IP packets. Note that while all tuples flowing on a single edge share a structure (schema), tuples on one edge may have very different structure than tuples on another – this is a significant distinction with the uniform IP packets of Click.

Figure 3.2 shows an example of a DN dataflow being executed at a single node. At the edges of the dataflow, a chain of network packet processing elements (encapsulated in the figure as *Network-In* and *Network-Out*) are used to process incoming and outgoing messages respectively. Figure 3.3 shows an example implementation of the networking-related elements. Both the *Network-In* and *Network-Out* portion of the dataflow comprise a longer sequence of network-related elements that implement functionality for sending and receiving messages using the UDP transmission protocol (*UDP-Tx* and *UDP-Rx*), and may also perform reliable transmission (*Retry* and *Ack*), and congestion control (*CC-Tx* and *CC-Rx* elements). These elements can be dynamically adapted (reordered, added or removed from the dataflow) based on the requirements of the declarative network [Condie et al., 2005].

Messages that arrive into the dataflow are buffered using queues, and demultiplexed (using the *Demux* element) via the relation name of each tuple into *strands*, and then duplicated (using the *Dup* element) into multiple strands that require input from the same relation. The strands are directly compiled from NDlog rules and implement the “logic” of the network. Each strand consists...
of a chain of elements implementing relational database operators like joins, selections, projections and aggregations. The use of joins is endemic in declarative networking because of the choice of NDlog: the unification (matching) of variables in the body of a rule is implemented in a dataflow by an equality-based relational join (equijoin). As shown in Figure 3.2, these strands take as input tuples that arrive via the network (output from the Dup element), local table updates (directly from the local tables) or local periodically generated events. The execution of strands either results in local table updates, or the sending of message tuples.

On the other side of the graph (shown as the Network-Out elements), message tuples are merged by a Mux element, queued and then sent based on their network destinations. Remote tuples are sent via an output queue to the network stack to be packetized, marshaled, and buffered by DN’s UDP transport, while tuples destined for local consumption are “wrapped around” to the Network-In element and queued along with other input tuples arriving over the network.

At runtime, the Network-In and Network-Out elements can be shared by multiple overlays that run concurrently. The system will compile them into a single dataflow for execution, where the Network-In and Network-Out elements will be shared among the different overlays.

### 3.2.1 DATAFLOW ELEMENTS

This section gives a brief overview of the suite of dataflow elements implemented in DN. As in Click, nodes in a DN dataflow graph can be chosen from a set of C++ objects called elements. In database systems these are often called operators, since they derive from logical operators in the relational algebra. DN provides the relational operators found in most database systems, as well as query processors like PIER [Huebsch et al., 2005]: selection, projection, streaming relational join operations such as pipelined hash-joins [Wilschut and Apers, 1991], “group-by,” and various aggregation functions.

One example of this is in DN’s networking stack. Systems like PIER [Huebsch et al., 2005] abstract details of transport protocols, message formats, marshaling, etc., away from the dataflow framework, and operators only deal with fully unmarshaled tuples. In contrast, DN explicitly uses the dataflow model to chain together separate elements responsible for socket handling, packet scheduling, congestion control, reliable transmission, data serialization, and dispatch [Condie et al., 2005].

A variety of elements form a bridge between the dataflow graph and persistent state in the form of stored tables. DN has elements that store incoming tuples in tables, lookup elements that can iteratively emit all tuples in a table matching a search filter, and aggregation elements that maintain an up-to-date aggregate (such as max, min, count, etc.) on a table and emit it whenever it changes. Tables are frequently shared between elements, although some elements generate their own private tables. For example, the element responsible for eliminating duplicate results in a dataflow uses a table to keep track of what it has seen so far. Finally, for debugging purposes, print elements that can be inserted to “watch” tuples based on table name (specified via a special "watch(tableName)" statement within the NDlog program) entering and leaving the dataflow.
3.3 NETWORK STATE STORAGE AND MANAGEMENT

Network state is stored in tables, which contain tuples with expiry times and size constraints that are declaratively specified at table creation time as described in Chapter 2. Duplicate entries (tuples) are allowed in tables, and the mechanisms for maintaining these duplicates differ based on whether they are hard-state or soft-state tables as defined in Chapter 2. In hard-state tables, a derivation count is maintained for each unique tuple, and each tuple is deleted when its count reaches zero. In soft-state tables, each unique tuple has an associated lifetime that is set based on the specified expiration of its table during creation time. Duplicates result in extension of tuple lifetime, and each tuple is deleted upon expiration based on its lifetime. The lifetimes of soft-state tuples are enforced by purging the soft-state tables of any expired tuples whenever they are accessed. Tables are named using unique IDs, and consequently can be shared between different queries and/or dataflow elements.

As basic data types, DN uses Values, and Tuples. A Value is a reference-counted object used to pass around any scalar item in the system; Value types include strings, integers, timestamps, and large unique identifiers. The Value class, together with the rules for converting between the various value types, constitute the concrete type system of DN. A Tuple is a vector of Values, and is the basic unit of data transfer in DN. Dataflow elements, described below, pass tuples between them, and tables hold sets of tuples.

Queries over tables can be specified by filters, providing an expressivity roughly equivalent to a traditional database query over a single table. In-memory indices (implemented using standard hash tables) can be attached to attributes of tables to enable quick equality lookups. Note that the table implementation—including associated indices—is a node-local construct.

3.3.1 RAPIDNET DECLARATIVE NETWORKING ENGINE

The RapidNet [RapidNet] declarative networking engine compile the NDlog programs into applications (with an execution model similar to Click [Kohler et al., 2000]) executable in ns-3 [ns-3], an emerging discrete event-driven simulator similar to the popular ns-2. Like its predecessor, ns-3 emulates all layers of the network stack, supporting configurable loss, packet queuing, and network topology models.

RapidNet has been used as an experimental platform [Liu et al., 2012, Muthukumar et al., 2009a] for a variety of declarative wireless routing protocols on the ORBIT [ORBIT] wireless testbed. The ability to run the same application in these two modes enables us to execute each NDlog program at scale in simulation and in an actual implementation running on a testbed.

In the initial design phase of RapidNet, a network protocol design is used as the basis for specifying the network protocol using the NDlog declarative networking language. In the simulation mode, the RapidNet compilation process generates ns-3 code from the NDlog protocol specifications. The generated code either runs as an ns-3 application, or replaces routing protocol implementations at the network layer. In the implementation mode, declarative networking specifications are directly executed and deployed either by using actual network sockets implemented on a real network across multiple machines. Simulation mode enables a comprehensive examination under various network
topologies and conditions, while the implementation mode allows different hosts in a testbed environment to execute the deployed system over a real network.

Since declarative networks share common functionalities such as the network stack, multiplexing tuple messages entering and leaving the dataflow, and database functionalities, all these utilities are defined in a shared RapidNet library. This enables one to simplify the compilation process to only the relevant database operations to implement the distributed dataflows for the corresponding declarative network specification. This also enables one to easily incorporate multi-query optimizations to share computations across declarative networks in future.

Figure 3.4: RapidNet demonstration [Muthukumar et al., 2009a,b] of a link-state routing protocol.

The RapidNet system takes input declarative network specifications which are automatically compiled to ns-3 code for execution in the ns-3 simulation and emulation modes. Network traces are directed to a ns-3 visualizer that will display the actual movement of nodes during the simulation, and side-by-side actual performance statistics of the protocol obtained from the ns-3 network statistics package.

Figure 3.4 shows an example execution of RapidNet system, based on a declarative mobile ad-hoc network (MANET) routing protocol [Liu et al., 2009a, 2011a]. The system (as demonstrated in [Muthukumar et al., 2009b]) visually shows the actual movements of nodes communicating via 802.11b ad-hoc mode using one of ns-3’s supported mobility models (e.g., random waypoint,
Brownian motion, hierarchical mobility, etc.). Each \textit{RapidNet} node incrementally updates its routes using a variety of declarative MANET routing protocols such as hazy-sighted link-state routing (HSLS) [Santivanez et al., 2001], optimized link-state routing (OLSR) [Clausen and Jacquet, 2003], dynamic source routing (DSR) [Johnson and Maltz, 1996], and summary-vector based epidemic routing [Vahdat and Becker, 2000]. Actual performance statistics of the protocol are also displayed side-by-side the actual protocol itself.

\subsection*{3.4 SUMMARY}

This chapter presents an overview of the DN declarative networking engine, with an emphasis on its architecture, various components (planner, dataflow installer, dataflow engine), dataflow framework and network state management. The next chapter describes the \textit{planner} component in greater detail, and shows how NDlog programs can be compiled into dataflow-based execution plans to implement the network protocols using the DN dataflow engine.
CHAPTER 4

Distributed Recursive Query Processing

One of the main challenges of using a declarative language is to ensure that the declarative specifications, when compiled and executed, result in correct and efficient implementations that are faithful to the program specifications. This is particularly challenging in a distributed context, where asynchronous messaging and the unannounced failure of participants make it hard to reason about the flow of data and events in the system as a whole. This chapter addresses this challenge by describing the steps required for the DN planner to automatically and correctly generate execution plans from the NDlog rules.

4.1 CENTRALIZED PLAN GENERATION

This section describes the steps required to generate execution plans of a centralized Datalog program using the semi-naïve (SN) fixpoint evaluation mechanism [Balbin and Ramamohanarao, 1987]. SN is the standard method used to evaluate Datalog programs correctly with no redundant computations. The Shortest-Path program (Figure 2.5 in Chapter 2) is used here as an example of how SN is achieved in the DN engine.

4.1.1 SEMI-NAÏVE EVALUATION

The first step in SN is the semi-naïve rewrite, where each Datalog rule is rewritten to generate a number of delta rules to be evaluated. Consider the following rule:

\[ p : - p_1, p_2, ..., p_n, b_1, b_2, ..., b_m. \] (4.1)

\( p_1, ..., p_n \) are derived predicates and \( b_1, ..., b_m \) are base predicates. Derived predicates refer to intensional relations that are derived during rule execution. Base predicates refer to extensional (stored) relations whose values are not changed during rule execution. The SN rewrite generates \( n \) delta rules, one for each derived predicate, where the \( k^{th} \) delta rule has the form:

\[ \Delta p_{\text{new}} : - p_{1}^{\text{old}}, ..., p_{k-1}^{\text{old}}, \Delta p_{k}^{\text{old}}, p_{k+1}, ..., p_n, b_1, b_2, ..., b_m. \] (4.2)

These delta rules are logically equivalent to rules of the form \( \Delta p_{\text{new}}^{j} : - p_{1}, p_2, ..., p_{k-1}, \Delta p_{k}^{\text{old}}, p_{k+1}, ..., p_n, b_1, b_2, ..., b_m, \) and have the advantage of avoiding redundant inferences within each iteration.
In each delta rule, $\Delta p_{k}^{\text{old}}$ is the delta predicate, and refers to $p_{k}$ tuples generated for the first time in the previous iteration. Here, $p_{k}^{\text{old}}$ refers to all $p_{k}$ tuples generated before the previous iteration. For example, the following rule $r2-1$ is the delta rule for the recursive rule $r2$ from the Datalog program shown in Figure 2.1 from Chapter 2:

$$
\Delta \text{path}^{\text{new}}(S, D, Z, C) : - \text{link}(S, Z, C_{1}), \Delta \text{path}^{\text{old}}(Z, D, Z_{2}, C_{2}), C = C_{1} + C_{2}.
$$

(4.3)

The only derived predicate in rule $r2$ is $\text{path}$, and hence one delta rule is generated. All the delta rules generated from the rewrite are then executed in synchronous rounds (or iterations) of computation, where input tuples computed in the previous iteration of a recursive rule execution are used as input in the current iteration to compute new tuples. Any new tuples that are generated for the first time in the current iteration are then used as input to the next iteration. This is repeated until a fixpoint is achieved (i.e., no new tuples are produced).

Algorithm 4.1 summarizes the basic semi-naïve evaluation used to execute these rules in the DN engine. In this algorithm, DN maintains a buffer for each delta rule, denoted by $B_k$. This buffer is used to store $p_k$ tuples generated in the previous iteration ($\Delta p_{k}^{\text{old}}$). Initially, $p_{k}$, $p_{k}^{\text{old}}$, $\Delta p_{k}^{\text{old}}$ and $\Delta p_{k}^{\text{new}}$ are empty. As a base case, all rules are executed to generate the initial $p_{k}$ tuples, which are inserted into the corresponding $B_{k}$ buffers. Each iteration of the while loop consists of flushing all existing $\Delta p_{k}^{\text{old}}$ tuples from $B_{k}$ and executing all the delta rules to generate $\Delta p_{j}^{\text{new}}$ tuples, which are used to update $p_{j}^{\text{old}}$, $B_{j}$ and $p_{j}$ accordingly. Note that only new $p_{j}$ tuples generated in the current iteration are inserted into $B_{j}$ for use in the next iteration. A fixpoint is reached when all buffers are empty.

**Algorithm 4.1** Semi-naïve Evaluation in DN

```plaintext
execute all rules
for each derived predicate $p_k$
    $B_k ← p_k$
end
while $\exists B_k . \text{size} > 0$
    $\forall B_k$ where $B_k . \text{size} > 0$, $\Delta p_{k}^{\text{old}} ← B_k . \text{flush}()$
    execute all delta rules
    for each derived predicate $p_j$
        $p_{j}^{\text{old}} ← p_{j}^{\text{old}} ∪ \Delta p_{j}^{\text{old}}$
        $B_j ← \Delta p_{j}^{\text{new}} - p_{j}^{\text{old}}$
        $p_j ← p_{j}^{\text{old}} ∪ B_j$
        $\Delta p_{j}^{\text{new}} ← ∅$
    end
end
```
4.1.2 DATAFLOW GENERATION

Algorithm 4.1 requires executing the delta rules at every iteration. These delta rules are each compiled into an execution plan, which is in the form of a DN dataflow strand, using the conventions of the DN dataflow framework described in Chapter 3. Each dataflow strand implements a delta rule via a chain of relational operators. In the rest of this chapter, the dataflow strand for each delta rule is referred to as a rule strand.

For each delta rule, each rule strand takes as input its delta predicate (prepended with $\Delta$). This input is then used as input to the strand which implements a sequence of elements implementing relational equijoins. Since tables are implemented as main-memory data structures with local indices over them, tuples from the stream are pushed into an equijoin element, and all matches in the table are found via an index lookup.

After the translation of the equijoins in a rule, the planner creates elements for any selection filters, which evaluate the selection predicate over each tuple, dropping those for which the result is false. In some cases, the dataflow can be optimized to push a selection upstream of an equijoin, to limit the state and work in the equijoin, following traditional database rules on the commutativity of join and selection.

Aggregate operations like $\text{MIN}$ or $\text{COUNT}$ are translated after equijoins and selections, since they operate on fields in the rule head. Aggregate elements generally hold internal state, and when a new tuple arrives, compute the aggregate incrementally. The final part of translating each rule is the addition of a “projection” element that constructs a tuple matching the head of the rule.

\[
\Delta \text{path}^{\text{new}}(S,D,Z,C) ::= \text{link}(S,Z,C_1), \Delta \text{path}^{\text{old}}(Z,D,Z_2,C_2), C = C_1 + C_2.
\]

Figure 4.1: Rule strand for delta rule r2-1 in DN.

Figure 4.1 shows the dataflow realization for delta rule r2-1. The rule is repeated above the dataflow for convenience. The example rule strand receives new $\Delta \text{path}^{\text{old}}$ tuples generated in the previous iteration to generate new paths ($\Delta \text{path}^{\text{new}}$) which are then “wrapped-around” and inserted into the path table (with duplicate elimination) for further processing in the next iteration. In effect, semi-naïve evaluation achieves the computation of paths in synchronous rounds of increasing hop counts, where paths that have been previously derived in the previous round are used to generate new paths in the next iteration.
4. DISTRIBUTED RECURSIVE QUERY PROCESSING

4.2 DISTRIBUTED PLAN GENERATION

In this section, we demonstrate the steps required to generate the execution plans for distributed NDlog rules. In Chapter 2, we introduced the concept of distributed NDlog rules, where the rule body predicates have different location specifiers. These distributed rules cannot be executed at a single node, since the tuples that must be joined are situated at different nodes in the network. Prior to the SN rewrite step, an additional localization rewrite step ensures that all body predicates for tuples to be joined are at the same node. After applying the localization rewrite to all distributed rules, all localized rules will have rule bodies that are locally computable and hence can be processed in a similar fashion as centralized Datalog rules.

4.2.1 LOCALIZATION REWRITE

To provide a high-level intuition for the localization rewrite, we consider the distributed rule sp2 from the Shortest-Path program presented in Chapter 2. This rule is distributed because the link and path predicates in the rule body have different location specifiers, but are joined by a common “Z” field. Figure 4.2 shows the corresponding logical query plan depicting the distributed join. The clouds represent an “exchange”-like operator [Graefe, 1990] that forwards tuples from one network node to another; clouds are labeled with the link attribute that determines the tuple’s recipient. The first cloud (link.@Z) sends link tuples to the neighbor nodes indicated by their destination address fields. The second cloud (path.@S) transmits new path tuples computed from the join for further processing, setting the recipient according to the source address field.

Based on the above distributed join, rule sp2 can be rewritten into the following two rules. Note that all predicates in the body of sp2a have the same location specifiers; the same is true of
sp2b. Since \texttt{linkD} is derived from the materialized table \texttt{link}, we need to also declare \texttt{linkD} via the \texttt{materialize} statement, and set its lifetime and size parameters to be the same as that of the \texttt{link} table.

\begin{verbatim}
materialize(linkD,infinity,infinity,1,2).
sp2a linkD(S,@Z,C) :- link(@S,Z,C).
sp2b path(@S,D,Z,P,C) :- link(@Z,S,C3),linkD(S,@Z,C1),path(@Z,D,Z2,P2,C2), C = C1 + C2, P = f_concatPath(S,P2).
\end{verbatim}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.3.png}
\caption{Localized rules for distributed rule $sp_2$.}
\end{figure}

The rewrite is achievable because the \texttt{link} and \texttt{path} predicates, although at different locations, share a common join address field.

### 4.2.2 DISTRIBUTED DATAFLOW GENERATION

\begin{verbatim}
sp2a \texttt{\Delta link}^{new}(S,@Z,C) := \texttt{\Delta link}^{old}(S,Z,C).
sp2b-1 \texttt{\Delta path}^{new}(S,D,Z,P,C) := link(@Z,S,C3), linkD(S,@Z,C1),
\quad \texttt{\Delta path}^{old}(@Z,D,Z2,P2,C2), C = C1 + C2, 
P = f_concatPath(S,P2).
sp2b-2 \texttt{\Delta path}^{new}(S,D,Z,P,C) := link(@Z,S,C3), \texttt{\Delta linkD}^{old}(S,@Z,C1),
\quad \texttt{path}(Z,D,Z2,P2,C2), C = C1 + C2, 
P = f_concatPath(S,P2).
\end{verbatim}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.4.png}
\caption{Delta rules and compiled rule strands for localized rules \texttt{sp2a} and \texttt{sp2b}.}
\end{figure}

After rule localization, the SN rewrite described in Section 4.1.1 is used to generate delta rules that are compiled into rule strands. In Figure 4.4, we provide an example of the delta rules and compiled rule strands for the localized rules \texttt{sp2a} and \texttt{sp2b} shown in Figure 4.3.

In addition to creating the relational operations described in the previous section on rule strand generation, the planner also constructs the other portions of the dataflow graph in order to support distribution. These are the network processing elements, which include multiplexing and demultiplexing tuples, marshaling, unmarshaling and congestion control. As with Click [Kohler et al.,
it also inserts explicit queue elements where there is a push/pull mismatch between two elements that need to be connected.

For simplicity, we represent the network packet processing, demultiplexing and multiplexing elements described in Section 3.2 as Network-In and Network-Out blocks in the figure, and only show the elements for the rule strands. Unlike the centralized strand in Figure 4.1, there are now three rule strands. The extra two strands (sp2a@S and sp2b-2@Z) are used as follows. Rule strand sp2a@S sends all existing links to the destination address field as linkD tuples. Rule strand sp2b-2@Z takes the new linkD tuples it received via the network, stores them using the Insert element. Each new linkD tuple (with duplicate elimination) is then used to perform a join operation with the local path table to generate new paths.

4.3 RELAXING SEMI-NAÏVE EVALUATION

In the distributed implementation, the execution of rule strands can depend on tuples arriving via the network, and can also result in new tuples being sent over the network. Traditional SN completely evaluates all rules on a given set of facts, i.e., completes the iteration, before considering any new facts. In a distributed execution environment where messages can be delayed or lost, the completion of an iteration in the traditional sense can only be detected by a consensus computation across multiple nodes, which is prohibitively expensive. Further, the requirement that many nodes complete the iteration together (a “barrier synchronization” in parallel computing terminology) limits parallelism significantly by restricting the rate of progress to that of the slowest node.

We address this by making the notion of iteration local to a node. New facts might be generated through local rule execution, or might be received from another node while a local iteration is in progress. The pipelined semi-naïve (PSN) extends SN to work in an asynchronous distributed setting, while generating the same results as SN. These techniques avoid duplicate inferences [Loo, 2006], which would otherwise result in generating unnecessary network messages.

4.3.1 PIPELINED SEMI-NAÏVE EVALUATION

Pipelined SN (PSN) relaxes SN to the extreme of processing each tuple as it is received. This provides opportunities for additional optimizations on a per-tuple basis, at the potential cost of batch, set-oriented optimizations of local processing. New tuples that are generated from the SN rules, as well as tuples received from other nodes, are used immediately to compute tuples without waiting for the current (local) iteration to complete.

Algorithm 4.2 shows the pseudocode for PSN. The \( k^{th} \) delta rule is of the form:

\[
p_j^{\text{new},i+1} : = p_1, \ldots , p_{k-1}, r_k^{\text{old},i}, p_{k+1}, \ldots , p_n, b_1, b_2, \ldots , b_m.
\]  

Each tuple, denoted \( t \), has a superscript \((\text{old/new}, i)\) where \( i \) is its corresponding iteration number in SN. Each processing step in PSN consists of dequeuing a tuple \( t_k^{\text{old},i} \) from \( Q_k \) and then using it as input into all corresponding rule strands. Each resulting \( t_j^{\text{new},i+1} \) tuple is pipelined, stored in
Algorithm 4.2 Pipelined SN (PSN) Evaluation.

execute all rules
for each \( t_k \in \) derived predicate \( p_k \)
\[ t_k.T \leftarrow \text{current\_time()} \]
\[ B_k \leftarrow t_k \]
end
while \( \exists Q_k.\text{size} > 0 \)
\[ t_k^{\text{old},i} \leftarrow Q_k.\text{dequeueTuple}() \]
for each delta rule execution
\[ \Delta p_j^{\text{new},i+1} := -p_1, p_2, ..., p_{k-1}, t_k^{\text{old},i}, p_{k+1}, ..., p_n, b_1, b_2, ..., b_m, \]
\[ t_{\text{old},i}.T \geq p_1.T, t_{\text{old},i}.T \geq p_2.T, ..., t_{\text{old},i}.T \geq p_{k-1}.T, t_{\text{old},i}.T \geq p_{k+1}.T, ..., \]
\[ t_{\text{old},i}.T \geq p_n.T, t_{\text{old},i}.T \geq b_1.T, ..., t_{\text{old},i}.T \geq b_2.T, ..., t_{\text{old},i}.T \geq b_m.T \]
for each \( i_{\text{new},i+1}^{\text{new},i+1} \in \Delta p_j^{\text{new},i+1} \)
\[ \text{if } i_{\text{new},i+1}^{\text{new},i+1} \notin p_j \]
\[ \text{then } p_j \leftarrow p_j \cup i_{\text{new},i+1}^{\text{new},i+1} \]
\[ i_{\text{new},i+1}^{\text{new},i+1}.T \leftarrow \text{current\_time()} \]
\[ Q_j.\text{enqueueTuple}(i_{\text{new},i+1}^{\text{new},i+1}) \]
end
end
end

Note that in a distributed implementation, \( Q_j \) can be a queue on another node, and the node that receives the new tuple can immediately process the tuple after the enqueue into \( Q_j \). For example, the dataflow in Figure 4.4 is based on a distributed implementation of PSN, where incoming path and linkD tuples received via the network are stored locally, and enqueued for processing in the corresponding rule strands.

To fully pipeline evaluation, we have also removed the distinctions between \( p_j^{\text{old}} \) and \( p_j \) in the rules. Instead, a timestamp (or monotonically increasing sequence number) is added to each tuple upon its arrival (or when inserted into its table), and the join operator matches each tuple only with tuples that have the same or older timestamp. In Algorithm 4.2, we denote the timestamp of each tuple as a \( T \) field (assigned via a system call \text{current\_time()}\)) and add additional selection predicates (highlighted in bold) to the \( k^{th} \) delta rule:
\[ p_j^{\text{new},i+1} := -p_1, ..., p_{k-1}, t_k^{\text{old},i}, p_{k+1}, ..., p_n, b_1, b_2, ..., b_m, \]
\[ t_{\text{old},i}.T \geq p_1.T, t_{\text{old},i}.T \geq p_2.T, ..., t_{\text{old},i}.T \geq p_{k-1}.T, t_{\text{old},i}.T \geq p_{k+1}.T, ..., \]
Each selection predicate $t^{old,i}_T \geq p_k.T$ ensures that the timestamp of $t^{old,i}$ is greater than or equal to the timestamp of a tuple $t \in p_k$. By relaxing SN, we allow for the processing of tuples immediately upon arrival, which is natural for network message handling. The timestamp represents an alternative “book-keeping” strategy to the rewriting used in SN to ensure no repeated inferences. Note that the timestamp only needs to be assigned locally, since all the rules are localized.

Given a rule with $n$ derived predicates and $m$ base predicates:

$$p : - p_1, p_2, ..., p_n, b_1, b_2, ..., b_m.$$ (4.5)

It is shown that PSN generates the same results as SN, and does not repeat any inferences [Loo, 2006].

In order to compute rules with aggregation (such as sp3), we utilize incremental fixpoint evaluation techniques [Ramakrishnan et al., 1992] that are amenable to pipelined query processing. These techniques can compute monotonic aggregates such as MIN, MAX and COUNT incrementally based on the current aggregate and each new input tuple.

### 4.4 PROCESSING IN A DYNAMIC NETWORK

In practice, the state of the network is constantly changing during the execution of NDlog programs. In contrast to transactional databases, changes to the network state are not isolated from NDlog programs while they are running. Instead, as in network protocols, NDlog rules are expected to perform dynamic recomputations to reflect the most current state of the network. To better understand the semantics in a dynamic network, we consider the following two degrees of dynamism.

- **Continuous Update Model:** In this model, we assume that updates occur very frequently—at a period that is shorter than the expected time for a typical program to reach a fixpoint. Hence, the query results never fully reflect the state of the network.

- **Bursty Update Model:** In this more constrained (but still fairly realistic) model, updates are allowed to happen during query processing. However, we make the assumption that after a burst of updates, the network eventually quiesces (does not change) for a time long enough to allow all the rule computations in the system to reach a fixpoint.

In this discussion, we focus on the bursty model, since it is amenable to analysis; the results on the bursty model provide some intuition as to the behavior in the continuous update model. The goal in the bursty model is to achieve a variant of the typical distributed systems notion of eventual consistency, customized to the particulars of NDlog: we wish to ensure that the eventual state of the quiescent system corresponds to what would be achieved by rerunning the rules from scratch in that state. We briefly sketch the ideas here, and follow up with details in the remainder of the section.
4.4. PROCESSING IN A DYNAMIC NETWORK

To ensure well-defined semantics, we use techniques from materialized view maintenance [Gupta et al., 1993], and consider three types of changes.

- **Insertion:** The insertion of a new tuple at any stage of processing can be naturally handled by (pipelined) semi-naïve evaluation.

- **Deletion:** The deletion of a base tuple leads to the deletion of any tuples that were derived from that base tuple (cascaded deletions). Deletions are carried out incrementally via (pipelined) semi-naïve evaluation by incrementally deriving all tuples that are to be deleted.

- **Update:** An update is treated as a deletion followed by an insertion. An update to a base tuple may itself result in derivation of more updates that are propagated via (pipelined) semi-naïve evaluation.

We further allow implicit updates by primary key, where a newly generated tuple replaces an existing tuple with the same primary key (but differs on other fields). The use of pipelined SN evaluation in the discussion can be replaced with buffered SN without changing our analysis. Since some tuples in hard-state tables may have multiple derivations, we make use of the count algorithm [Gupta et al., 1993] for keeping track of the number of derivations for each tuple, and only delete a tuple when the count is 0.

### 4.4.1 DATAFLOW GENERATION FOR INCREMENTAL VIEW MAINTENANCE

**Algorithm 4.3** Rule strands generation for incremental insertion of hard-state SN delta rules.

```plaintext
for each kth delta rule \( \Delta p : - p_1, p_2, ..., \Delta p_k, ..., p_n, b_1, b_2, ..., b_m \)
    \( RS_{ins} \leftarrow addElement(NULL, Insert-Listener(\Delta p_k)) \)
    for each derived predicate \( p_j \) where \( j \neq k \)
        \( RS_{ins} \leftarrow addElement(RS_{ins}, Join(p_j)) \)
    end
    for each base predicate \( b_j \)
        \( RS_{ins} \leftarrow addElement(RS_{ins}, Join(b_j)) \)
    end
    \( RS_{ins} \leftarrow addElement(RS_{ins}, Project(\Delta p)) \)
    \( RS_{ins} \leftarrow addElement(RS_{ins}, Network-Out) \)
    \( RS_{1ins} \leftarrow addElement(NULL, Network-In(\Delta p)) \)
    \( RS_{1ins} \leftarrow addElement(RS_{1ins}, Insert(\Delta p)) \)
end
```

Algorithms 4.3 and 4.4 show the pseudocode for generating the rule strands for a typical delta rule of the form \( \Delta p : - p_1, p_2, ..., \Delta p_k, ..., p_n, b_1, b_2, ..., b_m \), with \( n \) derived predicates and \( m \) base
The first algorithm generates rule strands \( RS_{ins} \) and \( RS_{1ins} \) for incremental insertions, and the second algorithm generates rule strands \( RS_{del} \) and \( RS_{1del} \) for incremental deletions. In both algorithms, the function \( RS \leftarrow addElement(RS, element) \) adds an element to the input rule strand \( RS \), and then returns \( RS \) itself. For correctness, each strand has to execute completely before another strand is executed.

In Algorithm 4.3, each \( RS_{ins} \) strand takes as input an \( Insert-Listener(\Delta pk) \) element that registers callbacks for new insertions in the \( pk \) table. Upon insertion of a new tuple \( tk \) into the \( pk \) table, the \( Insert-Listener \) element outputs the new tuple, which is then used to perform a series of joins with the other input tables in its rule strand to derive new \( p \) tuples. Each newly derived \( p \) tuple is then passed to a \( Project(\Delta p) \), and then sent out via the \( Network-Out \) element\(^2\). Each \( RS_{1ins} \) strand takes as input new \( p \) tuples that arrives via the network, and inserts these tuples into its local \( p \) table using the \( Insert(\Delta p) \) element.

Algorithm 4.4 Rule strands generation for incremental deletion of hard-state SN delta rules.

```plaintext
for each \( k^{th} \) delta rule \( \Delta p : = \{ p_1, p_2, \ldots, \Delta p_k, \ldots, p_n, b_1, b_2, \ldots, b_m \} \),
    \( RS_{del} \leftarrow addElement(NULL, Delete-Listener(\Delta pk, del)) \)
for each derived predicate \( p_j \) where \( j \neq k \),
    \( RS_{del} \leftarrow addElement(RS_{del}, Join(p_j)) \)
end
for each base predicate \( b_j \),
    \( RS_{del} \leftarrow addElement(RS_{del}, Join(b_j)) \)
end
\( RS_{del} \leftarrow addElement(RS_{del}, Project(\Delta p_{del})) \)
\( RS_{del} \leftarrow addElement(RS_{del}, Network-Out) \)
\( RS_{1del} \leftarrow addElement(NULL, Network-In(\Delta p_{del})) \)
\( RS_{1del} \leftarrow addElement(RS_{1del}, Delete(\Delta p)) \)
end
```

The \( RS_{del} \) and \( RS_{1del} \) strands in Algorithm 4.4 are generated in a similar fashion for incremental deletions. The \( RS_{del} \) strand takes as input tuples from a \( Delete-Listener(\Delta pk, del) \) element that outputs \( p_{del} \) tuples that have been deleted from the \( pk \) table. The \( RS_{1del} \) strand receives these tuples, and then delete those with the same values from the local \( p \) table using the \( Delete(\Delta p) \) element.

Figure 4.5 shows an example of compiled dataflow with rule strands for the delta rules sp2a, sp2b-1 and sp2b-2 that we presented earlier in Section 4.2. For each delta rule, applying Algorithms 4.3 and 4.4 result in several strands for incremental insertions and deletions. These are denoted by strand labels with subscripts \( ins \) and \( del \), respectively, in Figure 4.5. For example, strands \( sp2a_{ins}@S \) and \( sp2a_{del}@S \) are generated from the delta rule sp2a, and used to implement the incre-

\(^2\)Note that outbound \( p \) tuples generated by \( RS_{ins} \) that are destined for local consumption are “wrapped around” to the \( Network-In \) element as input to \( RS_{1ins} \) of the same dataflow locally, as described in Section 3.2.
4.4. PROCESSING IN A DYNAMIC NETWORK

Figure 4.5: Rule strands for the SN delta rules sp2a, sp2b-1 and sp2b-2 with incremental maintenance.

Incremental recomputation of linkD table based on modifications to the link table. Similarly, strands sp2b-1ins@S and sp2b-1del@S are generated from delta rule sp2b-1, and strands sp2b-2ins@S and sp2b-2del@S are generated from delta rule sp2b-2.

In handling rules with aggregates, we apply techniques for incremental computation of aggregates [Ramakrishnan et al., 1992] in the presence of updates. The arrival of new tuples may invalidate existing aggregates, and incremental recomputations can be cheaper than computing the entire aggregate from scratch. For example, the re-evaluation costs for MIN and MAX aggregates are shown to be $O(\log n)$ time and $O(n)$ space [Ramakrishnan et al., 1992].

4.4.2 CENTRALIZED EXECUTION SEMANTICS

Before considering the distributed execution semantics of NDlog programs, we first provide an intuitive example for the centralized case. Figure 4.6 shows a derivation tree for path(@e,d,a,[e,a,b,d],7) based on the Shortest-Path program. The leaves in the tree are the link base tuples. The root and the intermediate nodes are tuples recursively derived from the children inputs by applying either rules sp1 and sp2. When updates occur to the base tuples, changes are propagated up the tree to the root. The left diagram shows updating the tree due to a change in base tuple link(@a,b,5), and the right diagram shows the deletion of link(@b,e,1).

For example, when the cost of link(@a,b,5) is updated from 5 to 1, there is a deletion of link(@a,b,5) followed by an insertion of link(@a,b,1). This in turn results in the dele-
Figure 4.6: Derivation tree for derived path tuple from a to e.

Let $\text{FP}_p$ be the set of tuples derived using PSN under the bursty model, and $\text{FFP}_p$ be the set of tuples that would be computed by PSN if starting from the quiesced state. The following theorem holds [Loo, 2006].

Theorem (correctness): $\text{FP}_p = \text{FFP}_p$ in a centralized setting.

The proof requires that all changes (inserts, deletes, updates) are applied in the same order in which they arrive. This is guaranteed by the FIFO queue of PSN and the use of timestamps.

### 4.4.3 DISTRIBUTED EXECUTION SEMANTICS

In order for incremental evaluation to work in a distributed environment, it is essential that along any link in the network, there is a FIFO ordering of messages. That is, along any link literal $\text{link}(s,d)$, facts derived at node $s$ should arrive at node $d$ in the same order in which they are derived (and vice versa). This guarantees that updates can be applied in order. Using the same definition of $\text{FP}_p$ and $\text{FFP}_p$ as before, assuming the link FIFO ordering, the following theorem holds:

Theorem (distributed correctness): $\text{FP}_p = \text{FFP}_p$ in a distributed setting with FIFO links.

As a refinement to the basic count algorithm, each derived tuple can be shipped with a compact form of data provenance encoded using binary decision diagrams [Liu et al., 2009b]. With further enhancement [Nigam et al., 2011], it is shown, with detailed formal proofs, that the provenance-based approach ensures correctness even in the presence of message reordering in the network (i.e., no FIFO ordering requirement).
4.5 PROCESSING SOFT-STATE RULES

Up to this point in the chapter, we have focused on the processing of hard-state rules. In this section, we build upon the earlier techniques to process soft-state rules. Recall from Section 2.4 that a rule is considered soft-state if it contains at least one soft-state predicate in the rule head or body.

Soft-state relations are stored in soft-state tables within the DN engine as described in Section 3.3. Unlike hard-state tables, these tables store tuples only for their specified lifetimes and expire them in a manner consistent with traditional soft-state semantics. Timeouts can be managed lazily in soft-state tables by purging any expired soft-state tuples whenever tables are accessed. Unlike hard-state tables, these soft-state tables do not require maintaining a derivation count for each unique tuple. Instead, soft-state tuples that are inserted into their respective tables will extend the lifetime of identical tuples.

Algorithm 4.5 Rule strands generation for incremental refresh of soft-state delta rules.

for each delta rule $\Delta p : - p_1, p_2, \ldots, \Delta p_k, \ldots, p_n, b_1, b_2, \ldots, b_m$

$RS_{ref}$ ← addElement(NULL, Refresh-Listener($\Delta p_k$))

for each derived predicate $p_j$ where $j \neq k$

$RS_{ref}$ ← addElement($RS_{ref}$, Join($p_j$))

end

for each base predicate $b_j$

$RS_{ref}$ ← addElement($RS_{ref}$, Join($b_j$))

end

$RS_{ref}$ ← addElement($RS_{ref}$, Project($\Delta p$))

if ($p.loc = p_k.loc$) then

$RS_{ins}$ ← addElement($RS_{ins}$, Insert($\Delta p$))

else

$RS_{ref}$ ← addElement($RS_{ref}$, Network-Out)

$RS_{1ref}$ ← addElement(NULL, Network-Ins($\Delta p$))

end

end

end

Prior to applying the SN rewrite, the processing of soft-state rules requires the same localization rewrite step described in Section 4.2. After localization, the SN rewrite is applied to all soft-state rules. Consider a soft-state rule of the form:

$$p : - s_1, s_2, \ldots, s_m, h_1, h_2, \ldots, h_n, b_1, b_2, \ldots, b_o$$

(4.6)

where $s_1, s_2, \ldots, s_m$ are $m$ soft-state derived predicates, $h_1, h_2, \ldots, h_n$ are $n$ hard-state derived predicates, and $b_1, b_2, \ldots, b_o$ are $o$ base predicates. The SN rewrite generates $m + n$ delta rules, one for
each soft-state and hard-state derived predicate, where the $k^{th}$ soft-state delta rule takes as input $\Delta s_k$ tuples:

$$\Delta p : - s_1, s_2, ..., \Delta s_k, ..., s_m, h_1, h_2, ..., h_n, b_1, b_2, ..., b_o.$$  

In addition, the $j^{th}$ hard-state delta rule takes as input $\Delta h_j$ tuples:

$$\Delta p : - s_1, ..., s_k, ..., s_m, h_1, h_2, ..., \Delta h_j, ..., h_n, b_1, b_2, ..., b_o.$$  

Following the generation of delta rules, Algorithm 4.3 is used to generate the strands for incremental insertions in a similar fashion as hard-state rules. However, instead of using Algorithm 4.4 for generating strands for incremental deletions, Algorithm 4.5 is used to generate strands for incremental refreshes. The difference is due to soft-state rules being incrementally maintained using cascaded refreshes instead of cascaded deletions (see Section 2.4). In Algorithm 4.3, the strand RS$_{ref}$ takes as input a Refresh-Listener($\Delta p_{k,ref}$) element that outputs soft-state $p_k$ tuples that have been refreshed. These $p_k$ tuples are then used to derive $p$ tuples, which are then inserted by the RS$_{1,ref}$ into local $p$ tables. If $p$ is a soft-state relation, these new insertions will lead to further refreshes being generated, hence achieving cascaded refreshes.

**Figure 4.7:** Rule strands for distributed soft-state management of delta rules sp2a, sp2b–1 and sp2b–2.

For completeness, Figure 4.7 shows an example dataflow for a soft-state version of rule sp2, assuming that link and path have been declared as soft-state relations. In contrast to Figure 4.5, Refresh-Listener elements are used instead of Delete-Listener elements to generate soft-state refreshes.
4.5.1 EVENT SOFT-STATE RULES

Having presented the general steps required to process soft-state rules, in this section we focus on a special-case soft-state rule: the event soft-state rule presented in Section 2.4. As a quick recap, an event soft-state rule is of the form:

\[ p : - e, p_1, p_2, ..., p_n, b_1, b_2, ..., b_m. \]  

The rule body consists of one event predicate \( e \); the other predicates \( p, p_1, p_2, ..., p_n \) can either soft- or hard-state predicates, and \( b_1, b_2, ..., b_m \) are base predicates as before.

The dataflow generation for event soft-state rules is simplified due to the fact that events are not materialized. As we discussed in Section 2.4.2, NDlog’s event model does not permit two events to coincide in time. Hence, a rule with more than one event table would never produce any output. The only delta rule that generates any output tuples is the event delta rule that takes as input new \( e \) event tuples of the form:

\[ \Delta p : - \Delta e, p_1, p_2, ..., p_n, b_1, b_2, b_m. \]  

Since the delta predicate (prepended with \( \Delta \)) is essentially a stream of update events, none of the other delta rules generates any output and we can exclude them from dataflow generation.

```prolog
pp1 ping(@S,D,E) :- periodic(@S,E,5), link(@S,D).
pp2 pingMsg(S,@D,E) :- ping(@S,D,E), link(@S,D).
```

Figure 4.8: Rule strands for event soft-state rules pp1 and pp2.

Figure 4.8 shows the execution plan for rules pp1 and pp2 from the Ping-Pong program from Chapter 2. The first strand pp1@S takes as input a Periodic element that generates a periodic(@S,E,5) tuple every 5 s at node S with random event identifier E. This tuple is then used to join with link tuples to generate a ping event tuple that is then used in strand pp2@S to generate pingMsg event tuples.

The output of event soft-state rules can also be an aggregate computation, which is done on a per-event basis. Examples of such aggregate computations are shown in rules l2 and l3 from the declarative Chord specifications in Chapter 6. These rules compute aggregate MIN values stored in bestLookupDist and lookup tuples respectively, one for each input event.
Figure 4.9: Rule strand for rule 12, an event soft-state rule with aggregation.

Figure 4.9 shows the strand l2@NI generated for rule 12. This strand takes as input new lookup event tuples, which are then executed within the strand by joining with the node and finger tables to generate a set of matching output tuples. These output tuples are then used by the Aggregate element to compute a bestLookupDist tuple that stores the computed MIN value. Note that in this case, we have additional runtime checks in place in the dataflow execution to ensure that each lookup tuple is executed in its entirety within the strand to generate the bestLookupDist tuple before the strand processes the next lookup tuple.

4.6 SUMMARY

In this chapter, we described how NDlog programs can be processed by generating distributed dataflows. We first demonstrated how traditional semi-naive evaluation for centralized Datalog programs can be realized in our system, and further extend the techniques to handle distributed and soft-state NDlog rules. We further showed how we can ensure correct semantics of long-running NDlog programs in dynamic networks for both hard-state and soft-state rules. In the next chapter, we present the use of NDlog to express more complex overlay networks.
CHAPTER 5

Declarative Routing

Having given an overview of the NDlog language, this chapter focuses on declarative routing: the declarative specification of routing protocols for building extensible routing infrastructures. Declarative networking aims to strike a better balance between the extensibility and the robustness of a routing infrastructure. In addition to being a concise and flexible language for routing protocols, NDlog is amenable to static analysis, making it an attractive language for building safe, extensible routing infrastructures.

The chapter is organized as follows. First, Section 5.1 presents the motivation of declarative routing. Next, Section 5.2 provides an overview of declarative routing’s execution model. Section 5.3 illustrates the flexibility of NDlog through several declarative routing examples. The challenges of security are addressed in Section 5.4, and route maintenance under dynamic networks in Section 5.5. Finally, evaluation results are presented in Section 5.6.

5.1 MOTIVATION

Designing routing protocols is a difficult process. This is not only because of the distributed nature and scale of the networks, but also because of the need to balance the extensibility and flexibility of these protocols on one hand, and their robustness and efficiency on the other hand. One need look no further than the Internet for an illustration of these different tradeoffs.

Today’s Internet routing protocols, while arguably robust and efficient, are hard to change to accommodate the needs of new applications such as improved resilience and higher throughput. Upgrading even a single router is hard [Handley et al., 2005]. Getting a distributed routing protocol implemented correctly is even harder. And in order to change or upgrade a deployed routing protocol, one must get access to each router to modify its software. This process is made even more tedious and error prone by the use of conventional programming languages that were not designed with networking in mind.

Several solutions have been proposed to address the lack of flexibility and extensibility in Internet routing. Overlay networks allow third parties to replace Internet routing with new, “from-scratch” implementations of routing functionality that run at the application layer. However, overlay networks simply move the problem from the network to the application layer where third parties have control: implementing or updating an overlay routing protocol still requires a complete protocol design and implementation, and requires access to the overlay nodes.

On the other hand, a radically different approach, active networks [Tennenhouse et al., 1997], allows network packets to modify the operation of networks by allowing routers to execute code
5. DECLARATIVE ROUTING

within active network packets. This allows new functionality to be introduced to existing active networks without the need to have direct access to routers. However, due to the general programming models proposed for active networks, they present difficulties in both performance and the security and reliability of the resulting infrastructure.

Declarative routing provides a new point in this design space that aims to strike a better balance between the extensibility and the robustness of a routing infrastructure. With declarative routing, a routing protocol is implemented by writing a simple NDlog program, which is then executed in a distributed fashion at some or all of the nodes. Declarative routing can be viewed as a safer instantiation of active networks which aims to balance the concerns of expressiveness, performance and security, properties which are needed for an extensible routing infrastructure to succeed.

Declarative routing could evolve to be used in a variety of ways. One extreme view of the future of routing is that individual end-users (or their applications) will explicitly request routes with particular properties, by submitting the NDlog programs for route construction to the network. The safety and simplicity of declarative specifications would clearly be beneficial in that context. A more incremental view is that an administrator at an ISP might reconfigure the ISP’s routers by issuing an NDlog program to the network; different NDlog programs would allow the administrator to easily implement various routing policies between different nodes or different traffic classes. Even in this managed scenario, the simplicity and safety of declarative routing has benefits over the current relatively fragile approaches to upgrading routers. While this second scenario is arguably the more realistic one, declarative networking allows the other extreme in which any node (including end-hosts) can issue an NDlog program. We take this extreme position in order to explore the limits of the design.

5.2 EXECUTION MODEL

The routing infrastructure is modelled as a directed graph, where each link is associated with a set of parameters (e.g., loss rate, available bandwidth, delay). The router nodes in the routing infrastructure can either be IP routers or overlay nodes.

Figure 5.1 shows the architecture of a typical declarative router. Like a traditional router, a declarative router maintains a neighbor table, which contains the set of neighbor routers that this router can forward messages to, and a forwarding table in the forwarding plane, that is used to route incoming packets based on their destination addresses to neighboring nodes along a computed path.

The forwarding table is created by the routing protocol that executes on the control plane of each router. Each routing protocol takes as input any updates to the local neighbor table, and implements a distributed computation where routers exchange route information with neighboring routers to compute new routes.

In a declarative router, a declarative networking (DN) runtime engine runs on the control plane and takes as input local routing information such as the neighbor table. Instead of running a single routing protocol, the DN engine allows any routing protocols expressed in NDlog to be executed in a distributed fashion in the network. The results of the program are used to establish router forwarding
state which the routers use for forwarding data packets. Alternatively, the computed results can be
sent back to the party that issued the NDlog program, which can use these results to perform source
routing. Note that while the DN engine is used on the control plane in declarative routing, it can
be used more generally on the forwarding plane as well, as Chapter 6 demonstrates.

NDlog program dissemination and execution can happen in a variety of ways. In static sce-
narios, the program may be “baked in” to another artifact – e.g., router firmware or peer-to-peer
application software that is bundled with the DN engine. More flexibly, the program could be
disseminated upon initial declaration to all or some of the nodes running the DN engine. It may
be sufficient to perform dissemination via flooding, particularly if the program will be long-lived,
amortizing the cost of the initial flood. As an optimization, instead of flooding the program in the
network, one can instead “piggy-back” dissemination onto program execution: the program can be
embedded into the first data tuple sent to each neighboring node as part of executing the NDlog
program.

This execution model is based on a fully distributed implementation, where routes are computed
in a decentralized fashion. As an alternative, in a centralized design such as the Routing Control
Platform [Feamster et al., 2004], network information is periodically gathered from the routing
infrastructure, and stored at one or more central servers. Each program is sent to one or more of
these servers, which process the programs using their internal databases and set up the forwarding
state at the routers in the network.

During the execution of NDlog program, the neighbor table is periodically updated in response
to link failures, new links, or link metric changes. These updates are performed by the routers
themselves using standard mechanisms such as periodic pings. The DN engine is then notified of
updates to the neighbor table, and will incrementally recompute entries into the forwarding table.

Figure 5.1: A declarative router.
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In declarative routing, this simple interface is the only interaction required between the DN engine and the router’s core forwarding logic.

5.3 ROUTING PROTOCOLS BY EXAMPLES

To highlight the flexibility of NDlog, several examples of useful routing protocols expressed as NDlog rules are provided. These examples range from well-known routing protocols (distance vector, dynamic source routing, multicast, etc.) to higher-level routing concepts such as QoS constraints. This is by no means intended to be an exhaustive coverage of the possibilities of declarative routing protocols. The main goal here is to illustrate the natural connection between recursive programs and network routing, and to highlight the flexibility, ease of programming, and ease of reuse afforded by a declarative language. Routing protocols can be expressed in a few NDlog rules, and additional protocols can be created by simple modifications.

5.3.1 BEST-PATH ROUTING

Consider the base rules sp1 and sp2 used in the first Shortest-Path program from the previous chapter. That example computes all-pairs shortest paths. In practice, a more common program would compute all-pairs best paths. By modifying rules sp2, sp3 and sp4, the Best-Path program in Figure 5.2 generalizes the all-pairs shortest paths computation, and computes the best paths for any path metric C:

\[
\text{bp1 path}(S,D,D,P,C) \leftarrow \text{link}(S,D,C), \ P = f_{\text{init}}(S,D).
\]

\[
\text{bp2 path}(S,D,Z,P,C) \leftarrow \text{link}(S,Z,C1), \text{path}(Z,D,Z2,P2,C2), \\
\quad C = f_{\text{compute}}(C1,C2), \ P = f_{\text{concatPath}}(S,P2).
\]

\[
\text{bp3 bestPathCost}(S,D,\text{AGG}<C>) \leftarrow \text{path}(S,D,Z,P,C). \\
\text{bp4 bestPath}(S,D,P,C) \leftarrow \text{bestPathCost}(S,D,C), \text{path}(S,D,Z,P,C).
\]

Query bestPath(S,D,P,C).

Figure 5.2: Best-Path program.

The aggregation function (AGG) is left unspecified. By changing AGG and the function \( f_{\text{compute}} \) used for computing the path cost \( C \), the Best-Path program can generate best paths based on any metric including link latency, available bandwidth and node load. For example, if the program is used for computing the shortest paths, \( f_{\text{sum}} \) is the appropriate instantiation for \( f_{\text{compute}} \) in rule bp1, and MIN is the instantiation for AGG. The resulting bestPath tuples are stored at the source nodes, and are used by end-hosts to perform source routing. Instead of computing the best path between any two nodes, this program can be easily modified to compute all paths, any path or the Best-\( k \) paths between any two nodes.

To avoid generating path cycles, an extra predicate \( f_{\text{inPath}}(P2,S)=\text{false} \) can be added to rule bp2 to avoid computing best paths with cycles (e.g., when computing the longest latency.
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The rules from the Best-Path program can be further extended by including constraints that enforce a QoS requirement specified by end-hosts. For example, one can restrict the set of paths to those with costs below a loss or latency threshold $k$ by adding an extra constraint $C < k$ to the rules computing path.

5.3.2 DISTANCE-VECTOR ROUTING

```prolog
dv1 hop(@S,D,D,C) :- link(@S,D,C).
dv2 hop(@S,D,Z,C) :- link(@S,Z,C1), hop(@Z,D,W,C2), C = f_compute(C1,C2).
dv3 bestHopCost(@S,D,AGG<C>) :- hop(@S,D,Z,C).
dv4 bestPathHop(@S,D,Z,C) :- hop(@S,D,Z,C), bestHopCost(@S,D,C).
Query bestPathHop(@S,D,Z,C).
```

Figure 5.3: Distance-Vector program.

Figure 5.3 shows a program that expresses the distance vector protocol for customized best routes for any given path metric. Rules $dv1$ and $dv2$ are modified from rules $bp1$ and $bp2$ from the previous example to generate the hop tuple that maintains only the next hop on the path, and not the entire path vector $P$ itself. Rules $dv3$ and $dv4$ are added to set up routing state in the network: $bestPathHop(@S,D,Z,C)$ is stored at node $S$, where $Z$ is the next hop on the best path to node $D$.

The distance vector protocol has the count-to-infinity problem [Peterson and Davie, 2007], where link failures may result in long (sometimes infinite) protocol convergence times. By making a modification to rule $dv2$ and adding rule $dv5$, the well-known split-horizon with poison reverse [Peterson and Davie, 2007] fix to this problem can be applied as follows.

```prolog
#include(dv1,dv3,dv4)
dv2 hop(@S,D,Z,C) :- link(@S,Z,C1), hop(@Z,D,W,C2), C = C1 + C2, W != S.
Query bestPathHop(@S,D,Z,C).
```

Figure 5.4: Distance-Vector program with count-to-infinity fix in NDlog.

#include is a macro used to include earlier rules. Rule $dv2$ expresses that if node $Z$ learns about the path to $D$ from node $S$, then node $Z$ does not report this path back to $S$. Rule $dv5$ expresses that if node $Z$ receives a path tuple with destination $D$ from node $S$, then node $Z$ will send a path with destination $D$ and infinite cost to node $S$. This ensures that eventually node $S$ will not use $Z$ to get to $D$.

1The $W$ field in $dv2$ represents the next-hop to node $D$ from intermediate node $Z$, and can be ignored by node $S$ in computing its next hop to node $D$. 
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5.3.3 POLICY-BASED ROUTING

The previous examples all illustrate a typical network-wide routing policy. To restrict the scope of routing, e.g., by precluding paths that involve “undesirable” nodes. An example would be finding a path among nodes in an overlay network on PlanetLab that avoids nodes belonging to untruthful or flaky ISPs. Such policy constraints can be simply expressed by adding an additional rule.

```
#include(bp1,bp2)
pbr1 permitPath(@S,D,Z,P,C) :- path(@S,D,Z,P,C),
                        excludeNode(@S,W), f_inPath(P,W)=false.
Query permitPath(@S,D,P,C).
```

**Figure 5.5:** Policy-based routing program.

In this program, an additional table `excludeNode` is introduced, where `excludeNode(@S,W)` is a tuple that represents the fact that node `S` does not carry any traffic for node `W`. This table is stored at each node `S`.

If rules `bp1` and `bp2` are included as rules, `bestPath` tuples can be generated to meet the above policy. Other policy based decisions include ignoring the paths reported by selected nodes or insisting that some paths have to pass through (or avoid) one or multiple pre-determined set of nodes.

5.3.4 DYNAMIC SOURCE ROUTING

All of the previous examples use what is called right recursion, since the recursive predicates (e.g., `path` in the rules `sp2`, `bp2` and `dv2`) appears to the right of the matching `link`. Given that predicates are executed in a left-to-right order, the program semantics do not change if the order of `path` and `link` in the body of these rules are flipped, but the execution strategy does change. In fact, the Dynamic Source Routing (DSR) protocol [Johnson and Maltz, 1996] can be implemented by using left recursion as follows.

```
#include(bp1,bp3,bp4)
dsr2 path(@S,D,Z,P,C) :- path(@S,Z,W,P1,C1), link(@Z,D,C2),
                       C = f_compute(C1,C2), P = f_concatPath(P1,D).
Query bestPath(@S,D,P,C).
```

**Figure 5.6:** Dynamic Source Routing program.

Rule `bp1` produces new one-hop paths from existing link tuples as before. Rule `dsr2` matches the destination fields of newly computed path tuples with the source fields of link tuples. This requires newly computed path tuples be shipped by their destination fields to find matching links, hence ensuring that each source node will recursively follow the links along all reachable paths. Here,
the function \( f_{\text{concatPath}}(P, D) \) returns a new path vector with node \( D \) appended to \( P \). These rules can also be used in combination with \( \text{bpr1} \) and \( \text{bpr2} \) to generate the best paths. By adding two extra rules not shown here, the logic for sending each path on the reverse path from the destination to the source node can be expressed.

### 5.3.5 LINK STATE

To further illustrate the flexibility of this approach, consider a link-state protocol that moves route information around the network very differently from the best-path variants. The Link-State program, found in Figure 5.7, expresses the flooding of links to all nodes in the network.

\[
\begin{align*}
\text{ls1} & \quad \text{floodLink}(S, S, D, C) \ :- \ \text{link}(S, D, C). \\
\text{ls2} & \quad \text{floodLink}(M, S, D, C, N) \ :- \ \text{link}(N, M, C1), \ \text{floodLink}(N, S, D, C, W), \ M \neq W.
\end{align*}
\]

Figure 5.7: Link-State program.

\( \text{floodLink}(M, S, D, C, N) \) is a tuple storing information about \( \text{link}(S, D, C) \). This tuple is flooded in the network starting from source node \( S \). During the flooding process, node \( M \) is the current node it is flooded to, while node \( N \) is the node that forwarded this tuple to node \( M \).

Rule 1s1 generates a \( \text{floodLink} \) tuple for every link at each node. Rule 1s2 states that each node \( N \) that receives a \( \text{floodLink} \) tuple recursively forwards the tuple to all neighbors \( M \) except the node \( W \) that it received the tuple from. NDlog is based on the relational model that utilizes set computations, where duplicate tuples are not considered for computation twice. This ensures that no similar \( \text{floodLink} \) tuple is forwarded twice.

Once all the links are available at each node, a local version of the Best-Path program in Figure 5.2 is then executed locally using the \( \text{floodLink} \) tuples to generate all the best paths.

### 5.3.6 MULTICAST

The examples given so far support protocols for unicast routing. As a more complex example, NDlog is used to construct a multicast dissemination tree from a designated root node to multiple destination nodes that “subscribe” to the multicast group. The following Source-Specific-Multicast program sets up such a forwarding tree rooted at a source node \( a \) for group \( gid \):

For simplicity of exposition, this program utilizes the Best-Path program (rules \( \text{bp1} \), \( \text{bp2} \), \( \text{bp3} \), \( \text{bp4} \)) to compute the all-pairs best paths. We will discuss program optimization techniques to reduce the communication overhead for small multicast groups in Section 7.1.2.

Each destination node \( n \) joins the group \( gid \) with source \( a \) by issuing the program \( \text{join-Group}(n, a, gid) \). This results in the generation of the following derived tuples.

- **joinMessage(nodeID, prevNodeID, pathVector, source, gid)**. This tuple stores the multicast join message for group \( gid \). It is sent by every destination node along its best path to
5. DECLARATIVE ROUTING

```prolog
#include(bp1,bp2,bp3,bp4)
m1 joinMessage(@I,N,P,S,G) :- joinGroup(@N,S,G), bestPath(@N,S,P1,C),
    I = f_head(P1), P = f_tail(P1).
m2 joinMessage(@I,J,P,S,G) :- joinMessage(@J,K,P1,S,G), I = f_head(P1),
    P = f_tail(P1), f_isEmpty(P1) = false.
Query joinGroup(@N,a,gid)
```

Figure 5.8: Source-Specific-Multicast program.

the @source address of the group. At each intermediate node with address nodeID, prevNodeID
stores the address of the node that forwarded this tuple. pathVector is the remaining path that
this message needs to traverse in order to reach the source node.

- **forwardState(@nodeID, forwardNodeID, source, gid)**. This tuple represents source-specific
state of the multicast dissemination tree at each intermediate node with address nodeID. If
a message from source of multicast group gid is received at nodeID, it is forwarded to forwardNodeID.

Rules m1 and m2 create the joinMessage tuple at each participating destination node N,
and forward this tuple along the best path to the source node S. Upon receiving a joinMessage
tuple, rule M3 allows each intermediate node I to set up the forwarding state using the
forwardState(@I,J,S,G) tuple. The predicate function f_head(P) returns the next node in the
path vector P, and f_tail(P) returns the path vector P with the first node removed. f_isEmpty(P)
returns true if P is empty.

Instead of a source-specific tree, with minor modifications, we can construct core-based
trees [Ballardie et al., 1993]. Here, each participating node sends a join message to a designated
core node to build a shared tree rooted at the core. Messages are then unicast to the core, which
disseminates it using the shared tree.

5.4 SECURITY ISSUES

Security is a key concern with any extensible system [Bershad et al., 1995, Stonebraker, 1986]. In
the network domain, this concern is best illustrated by active networks which, at the extreme, allow
routers to download and execute arbitrary code.

Declarative routing’s approach essentially proposes NDlog as a Domain Specific Language
(DSL) [van Deursen et al., 2000] for programming the control plane of a network. DSLs typically
provide security benefits by having restricted expressivity. NDlog is attractive in this respect,
both because of its strong theoretical foundations, and its practical aspects. NDlog rules written
in the core\(^2\) Datalog language have polynomial time and space complexities in the size of the in-

\(^2\)Such a “core” language does not contain predicates constructed using function symbols.
5.5 ROUTE MAINTENANCE

During program execution, changes in the network might result in some of the computed routes becoming stale. These can be caused by link failures, or changes in the link metrics when these metrics are used in route computation. Ideally, the program should rapidly recompute a new route, especially in the case of link failures.

One solution is to simply recompute the programs from scratch, either periodically or driven by the party that has issued the programs. However, recompiling the program from scratch is expensive, and if done only periodically, the time to react to failures is a half-period on average.

The approach employed in declarative networking is to utilize long-running or continuous queries that incrementally recompute new results based on changes in the network. To ensure incremental recomputations, all intermediate states of each program are retained in the program processor until the program is no longer required. The intermediate states include any shipped tuples used in join computation, and any intermediate derived tuples.

As discussed in Section 5.2, each declarative router is responsible for detecting changes to its local information or base tables and reporting these changes to its local program processor. These base tuple updates result in the addition of tuples into base tables, or the replacement of existing
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base tuples that have the same unique key as the update tuples. The continuous queries then utilize
these updates and the intermediate state of rule executions to incrementally recompute some of their
derived tuples.

To illustrate, consider the Shortest-Path program that we introduce in Chapter 2. Figure 5.9 shows a simple four node network where all four nodes are running the Shortest-Path program. \(l(@S,D,C)\), \(p(@S,D,Z,P,C)\) and \(sp(@S,D,P,C)\) abbreviates \(\text{link}(S,D,C)\), \(\text{path}(S,D,Z,P,C)\) and \(\text{shortestPath}(S,D,P,C)\) respectively.

Prior to the link failure, assuming that all shortest paths between all pairs have been computed,
the figure shows the changes to the intermediate program states that led to the derivation of a new
shortest path from node \(a\) to \(d\) when node \(d\) fails. For simplicity, only the derived paths along the
solid lines are shown, even though the network connectivity is bidirectional (dashed lines). An invalid
path is denoted as one with infinite cost, although in practice, they are deleted from the
path table. When \(l(@c,d,1)\) is deleted, the following steps are taken to derive \(sp(@a,d,[a,b,d],3)\):

1. When neighbor \(c\) detects the failure of its link to \(d\) via a timeout, it generates an updated base
tuple \(l(@c,d,\infty)\) locally. This replaces the previous tuple \(l(@c,d,1)\).

2. All one-hop paths at node \(c\) that traverse through \(d\) are set to infinite costs. For example, node
\(c\) generates \(p(@c,d,d,[c,d],\infty)\).

3. \(p(@c,d,d,[c,d],\infty)\) is joined with \(l(@a,c,1)\) to produce \(p(@a,d,c,[a,c,d],\infty)\) which is sent to node \(a\).

4. Upon receiving \(p(@a,d,c,[a,c,d],\infty)\), node \(a\) computes a new shortest path
\(sp(@a,d,[a,b,d],3)\).

Figure 5.9: Derivation of alternative shortest path from node \(a\) to \(d\) when \(\text{link}(0,a,b,1)\) is deleted.
In this example, since the entire path vector is computed, one can check for potential cycles. The failure is propagated hop-by-hop. Hence, the time taken for any update to converge is proportional to the network diameter, and bounded by the time it takes for a program to be executed from scratch.

Updates to link costs are handled in a similar fashion, except that rather than setting the costs to infinity, they are recomputed based on the new link costs. The updated paths may trigger further computation. For example, when the cost of paths are changed, rules bpr1 and bpr2 of the Best-Path program will generate alternative best paths accordingly.

Chapter 4 revisits in detail the processing of continuous queries using both hard-state and soft-state incremental view maintenance techniques [Gupta et al., 1993].

5.6 EVALUATION

This section presents the performance evaluation of declarative routing protocols written in NDlog using P2 [P2]. The main metrics used in the evaluation are the following.

**Convergence time:** Given a quiesced network, the time taken for the network protocol to generate all its eventual network state. This is equivalent to achieving fixpoint during NDlog program execution, where there are no new derivations from all rules that are being executed.

**Communication overhead:** The number of bytes transferred for each network protocol in order to achieve convergence in a quiesced network. The experiment considers both aggregate communication overhead (MB), as well as per-node bandwidth (KBps).

As the input, network topologies are generated by GT-ITM [GT-ITM] (using the transit-stub configuration), a package that is widely used to model Internet topologies. A topology has four transit nodes, eight nodes per stub and three stubs per transit node. Latency between transit nodes is 50 ms, latency between transit nodes and their stub nodes is 10 ms, and latency between any two nodes in the same stub is 2 ms. The link capacity is set to 10 Mbps. Given the small size of the network, the topology is limited to four transit domains.

The declarative routing protocol runs as an overlay network over the base GT-ITM topology where each overlay node is assigned to one of the stub nodes. Each overlay node runs the P2 engine on one machine, and picks four randomly selected overlay neighbors which are stored as facts in each local link table.

5.6.1 SCALABILITY OF PATH-VECTOR PROTOCOL

The first experiment measures the performance of the system when all nodes are running the Shortest-Path program of Chapter 2, which implements the path-vector protocol used to compute the shortest latency paths between all pairs of nodes. The implementation uses the aggregate selections optimization to avoid sending redundant path tuples (Section 7.1.1), where the most recently computed shortest paths are batched and sent to neighboring nodes every 500 ms. The duration of 500 ms is chosen as it is an upper bound on the latency between any two nodes. This ensures that computed paths
at each iteration have sufficient time to be propagated and accumulated at every node for periodic aggregate selections to be most effective.

Figures 5.10 and 5.11 show the convergence latency and per-node communication overhead for the Shortest-Path program as the number of nodes increases from 25 to 200. The following observations are made.

- The convergence latency for the Shortest-Path program is proportional to the network diameter. This is expected because in a static network, the convergence time of the path vector protocol depends on the time taken to compute the longest shortest paths, which is bounded by the time taken for the computed shortest paths to propagate in the network (i.e., $500ms \times D_{\text{hop}}$, where $D_{\text{hop}}$ is the network diameter in terms of hop count).

- The per-node communication overhead increases linearly with the number of nodes. This is because each node needs to compute the shortest path to every other node in the network.

Both these observations are consistent with the scalability properties of the traditional distance vector and path vector protocols, suggesting that declarative routing does not introduce any fundamental overheads when used to implement traditional routing protocols.

### 5.6.2 Incremental Evaluation in Dynamic Networks

The next experiment examines the overhead of incrementally maintaining NDlog program results in a dynamic network. The same Shortest-Path program runs on 100 nodes over a period of time, and subject the network to bursty updates as described in Section 4.4. Each update burst involves randomly selecting 10% of all links, and then updating the cost metric by up to 10%.
The experiment adopts the shortest-path random metric, since executing the NDlog program using this metric is most demanding in terms of bandwidth usage and convergence time. This is because, as discussed in Section 7.1.1, aggregate selections are most useful for queries whose input tuples tend to arrive over the network out of order in terms of the monotonic aggregate – e.g., computing “shortest” paths for metrics that are not correlated with the network delays that dictate the arrival of the tuples during execution.

Figure 5.12 plots the per-node communication overhead, when applying a batch of updates every 10 s. Two points are worth noting. First, the time it takes the program to converge after a burst of updates is well within the convergence time of running the program from scratch. This is reflected in the communication overhead, which increases sharply after a burst of updates is applied, but then disappears long before the next burst of updates (Figure 5.12). Second, each burst peaks at 19 KBps, which is only 32% of the peak bandwidth and 28% of the aggregate bandwidth of the original computation. The results demonstrate the usefulness of performing incremental evaluation in response to changes in the network, as opposed to recomputing the queries from scratch.

The experiment is repeated using a more demanding update workload (Figure 5.13), where update intervals of 2 s and 8 s are interleaved, the former interval being less than the from-scratch convergence time of 3.6 s. Despite the fact that bursts are sometimes occurring faster than queries can run, bandwidth usage is similar to the less demanding update workload, peaking at 24 KBps and converging within the from-scratch convergence time.
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5.7 SUMMARY

This chapter motivates declarative routing, as a means to permit flexible routing over the Internet. Through several examples, we demonstrate that the NDlog language is natural for expressing a wide variety of network routing protocols. Interestingly, two important routing protocols (dynamic source routing and path vector protocols) differ only in the order in which predicates are evaluated. Section 5.6 measures the performance of declarative routing protocols such as the Best-Path program and validate that the scalability trends are similar to that of traditional approaches.
CHAPTER 6

Declarative Overlays

The previous chapter demonstrated the flexibility and compactness of NDlog for specifying a variety of routing protocols. In practice, most distributed systems are much more complex than simple routing protocols; in addition to routing, they typically also perform application-level message forwarding and handle the formation and maintenance of a network as well.

All large-scale distributed systems inherently use one or more application-level overlay networks as part of their operation. In some cases, the overlay is prominent: for example, file-sharing networks maintain neighbor tables to route queries. In other systems, the overlay or overlays may not be as explicit: for example, Microsoft Exchange email servers within an enterprise maintain an overlay network among themselves using a link-state algorithm over TCP for routing mail and status messages.

This chapter on declarative overlays demonstrates the use of NDlog to implement practical application-level overlay networks. In declarative overlays, applications submit to DN a concise NDlog program which describes an overlay network, and the DN system executes the program to maintain routing tables, perform neighbor discovery and provide forwarding for the overlay.

This chapter is organized as follows. Section 6.1 presents the execution model of declarative overlays. Two example NDlog programs are presented: the Narada [Chu et al., 2000] mesh for end-system multicast in Section 6.2, and the Chord [Stoica et al., 2001] distributed hash table in Section 6.3 respectively. Finally, evaluation results are shown in Section 6.4.

6.1 EXECUTION MODEL

A typical overlay network consists of three functionalities.

- **Routing** involves the computation and maintenance of routing tables at each node based on input neighbor tables. This functionality is typically known as the control plane of a network.

- **Forwarding** involves the delivery of overlay messages along the computed routes based on the destination addresses of the messages. This functionality is typically known as the forwarding plane of a network.

- **Overlay formation and maintenance** involves the process of joining an overlay network and maintaining the neighbor set at each node. The selected neighbors are used as input to the control plane for route computations.

In declarative routing presented in Chapter 5, NDlog programs are used solely for programming the control plane. Hence, all the previous routing examples consist of NDlog rules that compute
routes based on input links. On the other hand, in declarative overlays, NDlog programs implement the additional functionalities of forwarding and overlay formation and maintenance. As examples later in this chapter will illustrate, these programs are more complex due to the handling of message delivery, acknowledgments, failure detection and timeouts required by the additional functionalities. Not surprisingly, the programs presented in this section utilize soft-state data and soft-state rules introduced in Chapter 2 extensively. Despite the increased complexity, the NDlog programs are significantly more compact compared to equivalent C++ implementations.

![Figure 6.1: A Declarative Overlay Node.](image)

Figure 6.1 illustrates the execution model of declarative overlays. The DN system resides at the application level, and all messages are routed via the default Internet routing. In addition, by using the default Internet for routing between overlay nodes at the application level, it is assumed that there is full connectivity in the underlying network. Every node participating in the overlay network can send a message to another node via the underlying network, and there is an entry in the link table for every source and destination pair of nodes.

### 6.2 NARADA MESH

To provide a simple but concrete example of a declarative overlay, we first present a popular overlay network for End System Multicast (ESM) called Narada [Chu et al., 2000]. A typical ESM overlay consists of two layers: the first layer constructs and maintains a mesh connecting all members in the group, while the second layer constructs delivery trees on top of the mesh using typical multicast algorithms such as the distance vector multicast protocol (DVMRP) [Deering and Cheriton, 1990] (see Sections 5.3.2 and 5.3.6 for examples on DVMRP). This section focuses on the first layer: constructing a Narada-like mesh here as an example of the use of NDlog.
Briefly, the mesh maintenance algorithm works as follows. Each node maintains a set of
neighbors, and the set of all members in the group. Every member epidemically propagates keep-
alive messages for itself, associated with a monotonically increasing sequence number. At the same
time, neighbors exchange information about membership liveness and sequence numbers, ensuring
that every member will eventually learn of all the other group members’ liveness. If a member fails to
hear from a direct neighbor for a period, it declares its neighbor dead, updating its own membership
state and propagating this information to the rest of the population.

In addition, each node periodically probes a random group member to measuring the round-
trip latency. Based on the measured round-trip latencies to all group members, each node selects a
subset of the members to be its neighbors so that its predefined utility function is maximized. The
rest of this section shows how the mesh maintenance portion of Narada can be expressed in NDlog.
The definitions and initialization rules found in Figure 6.2 are used in Narada.

| materialize(sequence, infinity, 1, keys(2)). |
| materialize(neighbor, infinity, infinity, keys(2)). |
| materialize(member, 120, infinity, keys(2)). |
| e1 neighbor(@X,Y) :- periodic(@X,E,0,1), env(@X,H,Y), H = “neighbor”. |
| e2 member(@X,A,S,T ,L) :- periodic(@X,E,0,1), T = f_now(), S = 0, L = 1, A = X. |
| e3 member(@X,Y,S,T ,L) :- periodic(@X,E,0,1), neighbor(@X,Y), T = f_now(), |
| S = 0, L = 1. |
| e4 sequence(@X,Sequence) :- periodic(@X,E,0,1), Sequence = 0. |

Figure 6.2: Narada materialized tables and initialization rules.

The materialized table `member` is a soft-state relation with lifetime of 120 s, and have
unbounded size. The `neighbor` and `sequence` tables are hard-state relations. Though not ex-
licitly specified in the `materialize` statements, the `neighbor` contains tuples of the form
`neighbor(MyAddr, NeighborAddr)` and the `member` table contains tuples of the form mem-
ber(MyAddr, MemberAddr, MemberS, MemberInsertionTime, MemberLive). `MemberLive` is a
boolean indicating whether the local node believes a member is alive or has failed.

Rule `e1` initializes the neighbor table at each node based on its local `env` table which contains
its initial set of neighbors that have been preloaded into the table when the node is started. Rules
`e2-4` are used to initialize the `member` table and `sequence` tables respectively. As described in
Chapter 2, `periodic(@X,E,T,K)` is a built-in event predicate that is used to generate a stream of
periodic tuples at node `X` with random event identifier `E` every `T` seconds for up to `K` tuples. Hence,
the initialization rules `e1` and `e2` are only invoked once. Rule `e2-3` initialize the `member` table at
each node to itself and its initial set of neighbors. The `sequence(0X, Seq)` is a hard-state relation
of size 1, which stores a single tuple that keeps track of the current sequence number `Seq` used in
the gossip protocol.
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6.2.1 MEMBERSHIP LIST MAINTENANCE

At the start, each node begins with an initial neighbor set. Narada then periodically gossips with neighbors to refresh membership information. In Figure 6.3, the rules r1-r9 specify the rules for the periodic maintenance of the membership lists.

Rule r1 generates a requestEvent tuple every 5 s at node X. The request interval is set by the programmer and is used to determine the rate at which nodes in the Narada exchange membership lists.

Before a Narada node can refresh its neighbors’ membership lists, it must update its own sequence number, stored in the sequence table. Upon generating a refreshEvent, rule r2 creates a new refresh sequence number NewS for X by incrementing the currently stored sequence number NewS in the sequence table. Rule r3 updates the stored sequence number. Because sequence is a materialized table, whenever a new sequence tuple is produced, as is done with rule r3, it is implicitly inserted into the associated table. Since the primary key is the sequence number itself, this new sequence tuple replaces the existing tuple based on the update semantics defined in Chapter 2.

In rule r4, the refreshSeq(X, NewS) that is generated is then used to generate a refresh message tuple that is sent to each of X’s neighbors. Each refresh message tuple contains information about a membership entry as well as the current sequence number NewS.

Upon receiving the refresh message, rule r5 checks to see if the member Addr reported in the refresh message exists in the membership list. If such a member does not exist, the new member is inserted into the membership table (rule r6). If the member already exists, it is inserted into the membership table only if the sequence number in the refresh message is larger than that...
of the existing sequence number in the membership list (rule r7). The function \( f_{\text{now}}() \) is used to timestamp each member tuple stored.

To join the mesh, a new node need only know one member of the mesh, placing that member into its neighbor table. Rule r8 ensures that whenever a node receives a refresh message from its neighbor, it adds the sender to its neighbor set. This ensures that neighbor relationships are mutual.

### 6.2.2 NEIGHBOR SELECTION

There are two aspects of neighbor selection in Narada: first, evicting neighbors that are no longer responding to heartbeats (i.e., periodically generated ping messages that check whether nodes are still alive), and second, to select neighbors that meet certain user-defined criteria.

Figure 6.3 shows the rules 11–14 that can be used to check neighbor liveness. Every second, rule 11 initiates a neighbor check by which rule 12 declares dead a neighboring member that has failed to refresh for longer than 20 s. Dead neighbors are deleted from the neighbor table by rule 13 and rule 14 sets a dead neighbor’s member entry to be “dead” and further propagated to the rest of the mesh during refreshes.

```prolog
l1 neighborProbe(@X) :- periodic(@X,E,1).
l2 deadNeighbor(@X,Y) :- neighborProbe(@X), T = f_{\text{now}}(), neighbor(@X,Y), member(@X,Y,YS,YT,L), T - YT > 20.
l3 delete neighbor(@X,Y) :- deadNeighbor(@X,Y).
l4 member(@X,Neighbor,DeadSequence,T,Live) :- deadNeighbor(@X,Neighbor), member(@X,Neighbor,S,T1,L), Live = 0, DeadSequence = S + 1, T = f_{\text{now}}().
```

**Figure 6.4:** Rules for neighbor liveness checks.

Figure 6.5 shows the rules (n0–n3) for probing neighbors for latency measurements. Every 2 s, rule n0 picks a member at random with which to measure round-trip latency. Specifically, it

```prolog
n0 pingEvent(@X,Y,E,MAX<R>) :- periodic(@X,E,2), member(@X,Y,U,V,Z), R = f_{\text{rand}}().
n1 ping(@Y,X,E,T) :- pingEvent(@X,Y,E,MR), T = f_{\text{now}}().
n2 pong(@X,Y,E,T) :- ping(@Y,X,E,T).
n3 latency(@X,Y,T) :- pongX(X,Y,E,T1), T = f_{\text{now}}() - T1.
n5 neighbor(@X,Z) :- ugain(@X,Z,UGain), UGain > addThresh.
```

**Figure 6.5:** Rules for neighbor selection based on latency.
associates a random number with each known member, and then chooses the member associated
with the maximum random number. Recall that $\texttt{aggregate<fields>}$ denotes an aggregation function,
$\texttt{MAX}$ in this example. When a $\texttt{pingEvent}$ tuple is generated, rule $\texttt{n1}$ pings the randomly chosen
member stored in the event, rule $\texttt{n2}$ echoes that ping, and rule $\texttt{n3}$ computes the round-trip latency
of the exchange.

Nodes use such latency measurements—along with the paths computed by a routing protocol
operating on top of the mesh—to compute a utility function. A node may choose a new member to
add to its current neighbor set, if adding the new member increases its utility gain above an $\texttt{addition}
threshold$. Similarly, if the cost of maintaining a current neighbor is greater than an $\texttt{removal}
threshold$, the node may break its link with that neighbor.

Rules $\texttt{n4}$ and $\texttt{n5}$ in Figure 6.5 show how neighbor addition would work in an NDlog im-
plementation of Narada. Each node is assumed to maintain a routing table over the mesh which
contains for each member the next hop to that member and the cost of the resulting path; e.g.,
$\texttt{bestPathHop}(\texttt{S}, \texttt{D}, \texttt{Z}, \texttt{C})$ indicates that node $\texttt{S}$ must route via next-hop node $\texttt{Z}$ to get to des-
tination $\texttt{D}$ with a path latency of $\texttt{C}$. This $\texttt{bestPathHop}$ table can be computed by running the $\texttt{distance-vector}
protocol described in Section 5.3, taking as input the $\texttt{neighbor}$ table as the input
topology.

Rule $\texttt{n4}$ measures the utility gain that could be obtained if node $\texttt{Z}$ were to become $\texttt{X}$’s immediate
neighbor, as per the Narada definition [Chu et al., 2000]. For an individual destination $\texttt{Y}$, this is
computed by taking the latency of $\texttt{Z}$’s path to $\texttt{Y}$ and adding the latency between $\texttt{X}$ and $\texttt{Z}$ to it. If this
new path latency (assuming $\texttt{Z}$ becomes the next hop from $\texttt{X}$) is lower than the current latency of $\texttt{X}$’s
route to $\texttt{Y}$, then the relative decrease in latency contributes to the utility gain by adding neighbor $\texttt{Z}$. If this utility gain is above a threshold $\texttt{addThresh}$, then rule $\texttt{n5}$ adds this new neighbor.

### 6.3 CHORD DISTRIBUTED HASH TABLE

$\texttt{DN-Chord}$ is a full-fledged implementation of the Chord distributed hash table [Stoica et al., 2001]
implemented in 48 NDlog rules.

Chord is essentially a mechanism for maintaining a ring-based network and routing efficiently
on it. Figure 6.6 shows an example of a Chord ring. Each node in the Chord ring has a unique 160-
bit node identifier. For simplicity, the figure shows them as integers ranging from 0 to 60. Each
Chord node is responsible for storing objects within a range of key-space. This is done by assigning
each object with key $\texttt{K}$ to the first node whose identifier is equal to or follows $\texttt{K}$ in the identifier
space. This node is called the $\texttt{successor}$ of the key $\texttt{K}$. Note that data items and nodes are mapped into
the same identifier space. Therefore, each node also has a successor: the node with the next-higher
identifier. For example, the objects with keys 42 and 56 are served by node 58.

In Chord, each node maintains the IP addresses of multiple successors to form a ring of
nodes that is resilient to failure. Once a node has joined the Chord ring, it maintains network state
for $\texttt{S}$ successors in the ring (the $\texttt{succ}$ table) with the closest identifier distance to the node, and a
single predecessor (the $\texttt{pred}$ table of size 1) that stores the address of the node whose identifier just
Figure 6.6: A Chord ring with the network state for node 58 and 37, the finger entries for node 13, and stored objects 0, 24, 33, 42 and 56. The dotted lines denote the fingers for node 13.

precedes the node. The bestSucc stores the address of the successor whose identifier is the closest among all the successors to the current node. For example, if \( S = 2 \), the successors of node 58 in Figure 6.6 are 60 and 3, its best successor is 60 and its predecessor is 40.

In order to perform scalable lookups, each Chord node also holds a finger table, pointing at peers whose identifier distances exponentially increase by powers of two from itself. The entries in the finger table are used for efficiently routing lookup requests for specific keys. There are typically 160 finger entries at each Chord node with identifier \( N \), where the \( i^{th} \) entry stores the node that is responsible for the key \( 2^i + N \). In the example Chord ring, node 13 has finger entries to nodes 14, 16, 28 and 37, as denoted by the dotted lines.

6.3.1 CHORD NETWORK STATE

Figure 6.7 shows the materialized tables that are used to store the network state of DN-Chord. For convenience, we also show the corresponding schemas of the tables with their abbreviations are shown in Figure 6.8.

Each node stores a single landmark tuple denoting the address of the node that it uses to join the Chord network (this is known as the landmark node). It also stores a nodeID tuple that contains its node identifier. In addition, each node stores the network state for Chord in the succ, pred, bestSucc and finger tables. To illustrate, Figure 6.6 shows the network state stored at node 58 that consists of the following tuples:

- A nodeID(@IP58,58) tuple, where IP58 denotes the IP address of node 58, and 58 is the actual identifier itself;
materialize(nodeID, infinity, 1, keys(1)).  
materialize(landmark, infinity, 1, keys(1)).  
materialize(finger, 180, 160, keys(2)).  
materialize(uniqueFinger, 180, 160, keys(2)).  
materialize(bestSucc, 180, 1, keys(1)).  
materialize(succ, 30, 16, keys(2)).  
materialize(pred, infinity, 1, keys(1)).  
materialize(join, 10, 5, keys(1)).  
materialize(pendingPing, 10, infinity, keys(3)).  
materialize(fFix, 180, 160, keys(2)).  
materialize(nextFingerFix, 180, 1, keys(1)).

Figure 6.7: Materialized tables for DN-Chord.

<table>
<thead>
<tr>
<th>Predicate</th>
<th>Schema</th>
</tr>
</thead>
<tbody>
<tr>
<td>nodeID(@NI,N)</td>
<td>nodeID(@NodeIP,NodeID)</td>
</tr>
<tr>
<td>landmark(@NI,N)</td>
<td>landmark(@NodeIP,NodeID)</td>
</tr>
<tr>
<td>finger(@NI,BI,B)</td>
<td>finger(@NodeIP,EntryNumber,BestFingerIP,BestFingerID)</td>
</tr>
<tr>
<td>uniqueFinger(@NI,B)</td>
<td>uniqueFinger(@NodeIP,FingerIP)</td>
</tr>
<tr>
<td>bestSucc(@NI,N)</td>
<td>bestSuccessor(@NodeIP,NodeID)</td>
</tr>
<tr>
<td>succ(@NI,N)</td>
<td>successor(@NodeIP,NodeID)</td>
</tr>
<tr>
<td>pred(@NI,N)</td>
<td>predecessor(@NodeIP,NodeID)</td>
</tr>
<tr>
<td>join(@NI,E)</td>
<td>join(@NodeIP,EventID)</td>
</tr>
<tr>
<td>pendingPing(@NI,P,E,T)</td>
<td>pendingPing(@NodeIP,PingNodeID,EventID,PingTime)</td>
</tr>
<tr>
<td>lookup(@NI,K,R,E)</td>
<td>lookup(@currentNodeIP,Key,ResultingNode,EventID)</td>
</tr>
<tr>
<td>lookupResults(@NI,K,R,RI,E)</td>
<td>lookupResults(@RequestingNodeIP,Key,ResultKey,ResultNodeIP,EventID)</td>
</tr>
</tbody>
</table>

Figure 6.8: Predicates and corresponding schemas of materialized tables and lookup events used in DN-Chord.

- succ(@IP₅₈,60,IP₆₀) and succ(@IP₅₈,3,IP₄) tuples storing the immediate identifier and IP addresses of the two successors of node 58; and
- bestSucc(@IP₅₈,60,IP₆₀) and pred(@IP₅₈,40,IP₄₀) tuples storing the identifier and IP addresses of the best successor and predecessor of node 58.

The figure also shows similar network state for node 37, and the four finger entries for node 13: finger(@IP₁₃,0,14,IP₁₄), finger(@IP₁₃,1,16,IP₁₆), finger(@IP₁₃,3,28,IP₂₈) and finger(@IP₁₃,4,37,IP₃₇). Since there can be multiple finger entries pointing to the same node, the uniqueFinger table is used to keep track of only the unique nodes that are pointed by the finger entries.
In addition, there are other materialized tables such as join, pendingPing, fFix and nextFingerFix that are used to store intermediate state in the DN-Chord implementation. The rest of the section demonstrates how different aspects of Chord can be specified in NDlog: joining the Chord network, ring maintenance, finger maintenance and routing, and failure detection.

### 6.3.2 JOINING THE CHORD NETWORK

![Figure 6.9: Rules for initializing a Chord node.](image)

When a node is started, rules i1-i4 from Figure 6.9 can immediately deduce facts that set the initial state of the node. Rule i1 sets the pred to point to NIL indicating that there are no predecessors. Rule i2 initializes the nextFingerFix to be 0 for use in finger maintenance, as described in Section 6.3.4. Rule i3 initializes a landmark(@NI,LI) tuple in the landmark table of each node NI storing the address of the landmark node LI. This address is input to the DN system via a preloaded local env table. The landmark LI is set to NIL if the node itself is the landmark. Each node also stores a nodeID(@NI,N) tuple that contains the random node identifier N that is also preloaded from the local env table (Rule i4).

![Figure 6.10: Rules for joining the Chord ring.](image)

Figure 6.10 shows the rules for joining the Chord ring. To enter the ring, a node NI generates a joinEvent tuple locally (rule j1) whose arrival triggers rules j2-j6. Rule j2 creates a join tuple upon the arrival of the joinEvent tuple. In rule j3, if the landmark node is known (i.e., not NIL), a joinReq tuple is sent to the landmark node; otherwise rule j4 sets the node to point to itself as a successor, forming an overlay by itself and awaiting others to join in. When the landmark receives a joinReq tuple, rule j5 initiates a lookup from the landmark node for the successor of the joining
node’s identifier N, and set the return address of the lookup to be NI. If the lookup is successful, a lookupResults event is received at node NI. Rule j6 then defines the joining node’s successor (succ table) to be the result of the lookup.

### 6.3.3 CHORD RING MAINTENANCE

<table>
<thead>
<tr>
<th>Rule</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>sb2</td>
<td>succ(@NI,S1,SI1) :- periodic(@NI,E,10), succ(@NI,S,SI), succ(@SI,S1,SI1).</td>
</tr>
</tbody>
</table>

**Figure 6.11:** Rules for ring stabilization.

After joining the Chord network, each node performs the ring maintenance protocol in order to maintain a set of successors and a single predecessor. Candidate successors (and the single predecessor) are found during the stabilization phase of the Chord overlay maintenance. The rules specifying the stabilization phase in Figure 6.11. Stabilization is done periodically at time intervals of 15 s by the rules sb1, sb2 and sb3. Rule sb1 ensures that a node’s best successor’s predecessor is also stored in its successor table. In rule sb2, each successor periodically asks all of its successors to send it their own successors. In rule sb3, a node periodically notifies its successors about itself, allowing its successors to point their respective predecessors to the notifying node if it is closer in key-space compared to their current predecessors.

<table>
<thead>
<tr>
<th>Rule</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>n1</td>
<td>newSuccEvent(@NI) :- succ(@NI,S,SI).</td>
</tr>
<tr>
<td>n2</td>
<td>newSuccEvent(@NI) :- deleteSucc(@NI,S,SI).</td>
</tr>
<tr>
<td>n3</td>
<td>bestSuccDist(@NI,M,MIN &lt; D &gt;) :- newSuccEvent(@NI), nodeID(@NI,N), succ(@NI,S,SI), D = S - N - 1.</td>
</tr>
<tr>
<td>n5</td>
<td>finger(@NI,0,S,SI) :- bestSucc(@NI,S,SI).</td>
</tr>
</tbody>
</table>

**Figure 6.12:** Rules for computing best successor and first finger entry.

Based on the set of candidate successors obtained from stabilization, additional rules are required in order to select the best successor, and also evict successors that are no longer required. In Figure 6.12, rule n1 generates a newSuccEvent event tuple upon the insertion (refresh) of a new (existing) successor. Rule n2 generates a newSuccEvent for deletions of an existing successor.
The `newSuccEvent` event tuple triggers rules n3 and n4, which are used to define as “best” the successor among those stored in the `succ` stored table whose identifier distance from the current node's identifier is the lowest. Rule n5 further ensures that the first finger entry (used for routing lookups) is always the same as the best successor.

\[
\text{s1 succCount}(\text{@NI}, \text{COUNT} < * >) :- \text{newSuccEvent}(\text{@NI}), \text{succ}(\text{@NI}, S, SI).
\]

\[
\text{s2 evictSucc}(\text{@NI}) :- \text{succCount}(\text{@NI}, C), C > 4.
\]

\[
\text{s3 maxSuccDist}(\text{@NI}, \text{MAX} < D >) :- \text{nodeID}(\text{@NI}, N), \text{succ}(\text{@NI}, S, SI), \text{evictSucc}(\text{@NI}), D = S - N - 1.
\]

\[
\text{s4 delete succ}(\text{@NI}, S, SI) :- \text{nodeID}(\text{@NI}, N), \text{succ}(\text{@NI}, S, SI), \text{evictSucc}(\text{@NI}), D = S - N - 1.
\]

Figure 6.13: Rules for successor selection.

As new successors are discovered, successor selection only keeps those successors closest to a node in the table, evicting at each discovery the single remaining node (rules s1–s4 in Figure 6.13).

### 6.3.4 FINGER MAINTENANCE AND ROUTING

\[
\text{l1 lookupResults}(\text{@R}, K, S, SI, E) :- \text{nodeID}(\text{@NI}, N), \text{lookup}(\text{@NI}, K, R, E), \text{bestSucc}(\text{@NI}, S, SI), K \in (N, S].
\]

\[
\text{l2 bestLookupDist}(\text{@NI}, K, R, E, MIN < D >) :- \text{nodeID}(\text{@NI}, N), \text{lookup}(\text{@NI}, K, R, E), \text{finger}(\text{@NI}, I, B, BI), D = K - B - 1, B \in (N, K).
\]

\[
\text{l3 lookup}(\text{MIN < @BI >}, K, R, E) :- \text{nodeID}(\text{@NI}, N), \text{bestLookupDist}(\text{@NI}, K, R, E, D), \text{finger}(\text{@NI}, I, B, BI), D = K - B - 1, B \in (N, K).
\]

Figure 6.14: Rules for recursive lookups in Chord.

The finger table is used in Chord to route lookup requests. Figure 6.14 shows the three rules that are used to implement lookups in Chord. Each `lookup(@NI, K, R, E)` event tuple denotes a lookup request at node NI for key K, originates from node R with event identifier E.

From the earlier introduction to the Chord protocol, all lookup requests for key K seek the node whose identifier is the immediate successor on the ring of K. Rule l1 is the base case, returning a successful lookup result if the received lookup seeks a key K found between the receiving node’s identifier and that of its best successor. Rule l2 is used in non-base cases, to find the minimum distance (in key identifier space modulo 2^{160}) from the local node’s fingers to K for every finger node BI whose identifier B lies between the local node’s identifier N and K. Rule l3 then selects one of the finger entries with the minimum distance to key K as the target node BI to receive the lookup.
request. Since there can be multiple such finger entries, the \( \text{min}_{\text{BI}} \) aggregate ensures that only one of the finger entries receives the forwarded lookup.

\[
\begin{align*}
\text{f1} & \quad \text{fFix}(\text{NI}, E, I) :- \text{periodic}(\text{NI}, E, 10), \text{nextFingerFix}(\text{NI}, I). \\
\text{f2} & \quad \text{fFixEvent}(\text{NI}, E, I) :- \text{fFix}(\text{NI}, E, I).
\end{align*}
\]

\[
\begin{align*}
\text{f3} & \quad \text{lookup}(\text{NI}, K, \text{NI}, E) :- \text{fFixEvent}(\text{NI}, E, I), \text{nodeID}(\text{NI}, N), K = 0x1I < < I + N. \\
\text{f4} & \quad \text{eagerFinger}(\text{NI}, I, B, BI) :- \text{fFix}(\text{NI}, E, I), \text{lookupResults}(\text{NI}, K, B, BI, E).
\end{align*}
\]

\[
\begin{align*}
\text{f5} & \quad \text{finger}(\text{NI}, I, B, BI) :- \text{eagerFinger}(\text{NI}, I, B, BI). \\
\text{f6} & \quad \text{eagerFinger}(\text{NI}, I, B, BI) :- \text{eagerFinger}(\text{NI}, I, I, B, BI), \quad \text{nodeID}(\text{NI}, N), I = I + 1, \\
& \quad K = 0x1I < < I + N, K \in (N, B), \text{NI} \neq \text{BI}. \\
\text{f7} & \quad \text{delete fFix}(\text{NI}, E, I1) :- \text{eagerFinger}(\text{NI}, I, B, BI), \quad \text{fFix}(\text{NI}, E, I1), \\
& \quad I > 0, I1 = I - 1. \\
\text{f8} & \quad \text{nextFingerFix}(\text{NI}, 0) :- \text{eagerFinger}(\text{NI}, I, B, BI), (I = 159) \parallel (BI = \text{NI}). \\
\text{f9} & \quad \text{nextFingerFix}(\text{NI}, I) :- \text{eagerFinger}(\text{NI}, I, B, BI), \quad \text{nodeID}(\text{NI}, N), I = I + 1, \\
& \quad K = 0x1I < < I + N, K \in (B, N), \text{NI} \neq \text{BI}. \\
\text{f10} & \quad \text{uniqueFinger}(\text{NI}, BI) :- \text{finger}(\text{NI}, I, B, BI).
\end{align*}
\]

**Figure 6.15:** Rules for generating finger entries.

Figure 6.15 shows the rules for generating the entries in the `finger` table. There are two additional materialized tables `fFix` and `nextFingerFix` that store intermediate state for the finger fixing protocol. The `nextFingerFix` table stores one tuple `nextFingerFix(\text{NI}, I)` that stores the next finger entry `I` to be picked for fixing at node `\text{NI}`.

Every 10 s, rule `f1` selects the `I` finger to fix, and then generates a `fFix(\text{NI}, E, I)` tuple that denotes that the `I` finger is selected for fixing with event identifier `E`. This results in the generating of a `fFixEvent(\text{NI}, E, I)` event tuple in rule `f2` which will generate a `lookup` request for key \( K = 2^I + N \) with the corresponding event identifier `E`. When the lookup succeeds, rule `f4` receives a `lookupResults` event tuple, which it then uses to update all the corresponding finger entries (\( f5-6 \)). Rules `f7-f9` then deletes the `fFix` tuple, and then increments the `I` field of `nextFingerFix` by 1 for fixing the next finger entry in the next period. Rule `f10` sets the `uniqueFinger` based on new finger entries.

### 6.3.5 FAILURE DETECTION

Figure 6.16 shows the rules that a node utilizes for sending keep-alive messages to its neighbors. The rules are similar to that of the `Ping-Pong` program presented in Chapter 2. At regular intervals of 5 s, each node generates one `pendingPing` tuple for each one of its neighbors (rules `pp1`, `pp2` and `pp3`). This results in `pingReq` messages that are periodically (every 3 s as indicated in rule `pp3`)
6.3. CHORD DISTRIBUTED HASH TABLE

Figure 6.16: Rules for sending keep-ales.

<table>
<thead>
<tr>
<th>Rule</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp1</td>
<td>pendingPing(@NI,SI,E1,T) :- periodic(@NI,E,5), succ(@NI,S,SI),</td>
</tr>
<tr>
<td></td>
<td>E1 = f_rand(), SI != NI, T = f_now().</td>
</tr>
<tr>
<td>pp2</td>
<td>pendingPing(@NI,PI,E1,T) :- periodic(@NI,E,5), pred(@NI,P,PI),</td>
</tr>
<tr>
<td></td>
<td>E1 = f_rand(), PI != &quot;NIL&quot;, T = f_now().</td>
</tr>
<tr>
<td>pp3</td>
<td>pendingPing(@NI,FI,E1,T) :- periodic(@NI,E,5), uniqueFinger(@NI,FI),</td>
</tr>
<tr>
<td></td>
<td>E1 = f_rand(), T = f_now().</td>
</tr>
<tr>
<td>pp4</td>
<td>pingResp(@RI,NI,E) :- pingReq(@NI,RI,E).</td>
</tr>
<tr>
<td>pp5</td>
<td>pingReq(@PI,NI,E) :- periodic(@NI,E1,3),</td>
</tr>
<tr>
<td></td>
<td>pendingPing(@NI,PI,E,T).</td>
</tr>
<tr>
<td>pp6</td>
<td>delete pendingPing(@NI,SI,E,T) :- pingResp(@NI,SI,E), pendingPing(@NI,SI,E,T).</td>
</tr>
</tbody>
</table>

Figure 6.17: Rules for failure detection of successors, predecessors and fingers.

<table>
<thead>
<tr>
<th>Rule</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>fd1</td>
<td>nodeFailure(@NI,PI,E1,D) :- periodic(@NI,E,1), pendingPing(@NI,PI,E1,T),</td>
</tr>
<tr>
<td></td>
<td>T1 = f_now(), D = T-T1, D &gt; 7.</td>
</tr>
<tr>
<td>fd2</td>
<td>delete pendingPing(@NI,PI,E,T) :- nodeFailure(@NI,PI,E,D),</td>
</tr>
<tr>
<td></td>
<td>pendingPing(@NI,PI,E,T).</td>
</tr>
<tr>
<td>fd3</td>
<td>deleteSucc(@NI,SI) :- succ(@NI,S,SI), nodeFailure(@NI,S,E,D).</td>
</tr>
<tr>
<td>fd5</td>
<td>pred(@NI, &quot;NIL&quot;,&quot;NIL&quot;) :- pred(@NI,P,PI), nodeFailure(@NI,PI,E,D).</td>
</tr>
<tr>
<td>fd6</td>
<td>delete finger(@NI,I,B,BI) :- finger(@NI,I,B,BI), nodeFailure(@NI,BI,E,D).</td>
</tr>
<tr>
<td>fd7</td>
<td>delete uniqueFinger(@NI,FI) :- uniqueFinger(@NI,FI), nodeFailure(@NI,FI,E,D).</td>
</tr>
</tbody>
</table>

sent to the respective neighbors for the lifetime of each pendingPing tuple. These pendingPings are deleted upon receiving the corresponding pingResp messages.

Figure 6.17 shows the rules for detecting failure of successors, predecessors and fingers. Here, rule fd1 generates nodeFailure events when there are outstanding pendingPing tuples that are unanswered after a period of time. The choices of 7 s in rule fd1 and 3 s in rule pp5 determine the frequency in which pingReq messages are sent, and the number unanswered replies that are required before concluding that a node is “dead.” In this example, a node is considered “dead” if there are two successive unanswered pingReq messages. The nodeFailure event then results in deletion of pendingPing, succ and finger entries, and resetting the single pred entry (rules fd3–fd7). A deleteSucc event is generated to allow the recomputation of the best successor in rules n2–n5.

6.3.6 SUMMARY OF CHORD

Chord is specified in only 48 rules, which is two orders of magnitude less code compared to an equivalent C++ implementation [MIT Chord]. In addition, in order to deal with issues related to
message delivery, acknowledgments, failure detection and timeouts, there is extensive use of soft-state tables and soft-state rules presented in Chapter 2.

As a summary, in addition to the `materialize` statements and initialization rules i1–i4, the NDlog rules for Chord can be categorized into three functionalities of a typical overlay network that we presented earlier.

- **Overlay formation and maintenance**: Rules j1–j6 are used by a node joining the Chord network via a landmark. Once a node has joined the ring, rules sb1–sb3 are used to execute the ring stabilization to learn about new successors and refine the predecessor. Based on the successors learned, rules n1–n5 are used for selecting the best successor, and rules s1–s4 are used for evicting unnecessary successors. To ensure that all overlay neighbors are alive, rules pp1–pp6 and fd1–fd7 for periodically pinging all successors, predecessors and finger entries, and deleting them if they do not respond to heartbeats.

- **Routing**: Given the basic ring network, rules f1–f10 for generating finger table entries that ensures scalable lookups.

- **Forwarding**: With the finger table in place, rules 11–13 are used for routing lookup requests via the finger table.

**Overlay formation** constitutes the majority of Chord rules, and clearly illustrates the additional challenges in specifying declarative overlays compared to the relatively simpler NDlog programs for implementing routing protocols presented in Chapter 5.

### 6.4 EVALUATION

This section presents performance results of the Narada mesh and the DN-Chord DHT. The experiments are carried out using P2 [P2], on 100 machines on the Emulab testbed [Emulab]. In both overlay networks, the latency between any two overlay nodes is set to 100 ms, and link capacity is set to 10 MBps.

#### 6.4.1 NARADA MESH FORMATION

The first experiment evaluates the Narada specifications on mesh formation. The experiment consists of 100 Narada nodes, one on each Emulab node. All nodes join the network over a span of 10 s. Each Narada node has an initial set of neighbors, and at regular intervals of 5 s, propagate its entire membership list to its neighbors. The measurement metrics include the per-node bandwidth (KBps) of periodically sending the membership list in the steady state, and also the convergence time (seconds) taken for all Narada nodes have achieved full membership knowledge of the entire network.

Figure 6.18 shows the CDF of membership at each node as a fraction of the entire network size over time (seconds) for a network size of 100 for two experimental runs (NS=2, NS=4) where
the number of neighbors that each node has is varied (2 and 4 neighbors). Each data point \((x, y)\) shows the average fraction \(y\) of the network that each node knows at time \(x\). Upon convergence, all nodes learn about every other node in the network (i.e., \(y = 1\)).

The figure show that the Narada implementation converges on the sparser network \((NS = 2)\) within 60 s, while requiring less than 40 s to converge on the denser network \((NS = 4)\). The convergence time includes the initial 10 s as nodes join the Narada network. These evaluation results demonstrate the tradeoffs between bandwidth and convergence in propagating the membership list — the faster convergence of the denser network comes at the expense of bandwidth utilization (33 \(KBps\)) as compared to 13 \(KBps\) for the sparser network.

### 6.4.2 CHORD DHT

The next set of experiments focuses on measuring the specification for the Chord Distributed Hash Table. Chord serves as a good stress test of the declarative overlays, being relatively complex compared to other overlay examples like gossip and end-system multicast. Chord also has the advantage of being well-studied. The Chord deployment on the Emulab testbed [Emulab] consists of 100 machines (64-bit Xeon 3000 series with 2 GB memory) executing up to 500 Chord instances (5 Chord processes running on each Emulab machine). The same network topology as the Narada experiment is utilized.

#### Static Network Validation

The first round of experiments is to validate the high-level characteristics of the Chord overlay, using a uniform workload of DHT “lookup” requests to a static set of nodes in the overlay, with no nodes joining or leaving. This is somewhat unrealistic but it allows to validate the static properties...
Each experiment starts with a landmark node, and all other nodes join the landmark node at regular intervals. Once all the nodes have joined the Chord overlay, lookups are issued every 15 s simultaneously (with the same lookup key $K$) from 10 nodes.

All lookup requests return successfully with the lookup requests. In addition, all lookups achieve 100% consistency, where all lookup requests for the same key issued from different nodes return identical results. Figures 6.19, 6.20, and 6.21 report the quantitative performance results.

Figure 6.19 shows the hop count distribution for the workload. Except for a few outliers, 99% of all lookups complete within 10 hops. The average hop count of lookups are 3.3, 4.0 and 4.5 for node sizes of 100, 300 and 500 respectively, approximating the theoretical average of $0.5 \times \log_2(N)$, where $N$ is the number of nodes.

Figure 6.20 shows the CDF of lookup latencies for different network sizes. As expected, the average latency increases in proportion to the average lookup hop count for each network size. On a 500 node static network, 99% of all lookups complete in less than 3.4 s. The average (median) latencies are 0.81 s (0.72 s), 0.92 s (0.82 s) and 1.09 s (0.98 s) for node sizes of 100, 300 and 500, respectively. The average and median latency numbers are within the same order of magnitude as the published numbers [Stoica et al., 2001] of the MIT Chord deployment.

Figure 6.21 shows the per-node bandwidth (KBps) consumption over time (in seconds) for a static DN-Chord network where fingers are fixed every 10 s, and ring stabilization (exchange of successors and predecessors among neighbors) happen every 10 s. Each node periodically sends ping messages to neighbors every 3 s. After an initial linear increase in bandwidth as nodes join the Chord ring, the bandwidth utilization stabilizes at 0.34 KBps, well within the published bandwidth consumption of 1 KBps [Rhea et al., 2004] of other high consistency and low latency DHTs.
Churn Performance

The second round of experiments focuses on the performance of the Chord implementation under varying degrees of membership churn. Again, the goal is to validate that the compact declarative specification of Chord faithfully captures its salient properties following the methodology in the Bamboo system [Rhea et al., 2004]. The experiment is performed on a 100 node Chord network. Once the network is stable, churn is induced for 20 min as follows. Periodically, a randomly selected node fails. Upon each node failure, a new node immediately joins the Chord network with a different node identifier. The interval between every node failure/restart event varies to achieve different average node session times (8, 16, 47 and 90 min).

In the steady state under constant churn, lookups for the same key are issued simultaneously from 10 different nodes every 15 s. Following the methodology in Bamboo [Rhea et al., 2004], a consistent lookup is defined as when a majority of the lookups (>5) see a consistent result that points to the same node that owns the key. For each group of 10 lookups, the maximum fraction of lookups that share a consistent result is computed.

Chord’s churn parameters are set as follows: (1) the fix finger and ring-stabilization periods are both set to 10 s as before; (2) each node periodically send ping messages to neighbor nodes every 3 s, and remove entries from the local neighbor tables if they do not respond to two successive pings.

Figure 6.22 shows the CDF (log-scale for Y-axis) for the consistent fraction of lookups, which is defined as the fraction of lookups with consistent result for each group of simultaneous lookups. To interpret the graph, each data-point (x, y) shows the fraction y of lookups with lookup consistency less than x. The results show that DN-Chord does well under low churn (session times of 90 min and 47 min), generating 99% and 96% consistent lookups. Under high churn (session times of 16 min and 8 min), it also performs well, producing 95% and 79% consistent lookups.
Figure 6.23 shows the CDF of the lookup latencies for different churn rates. At low churn rates, the lookup latencies are similar to those measured under a stable Chord network with no churn. At high churn rates, the average lookup latency increased from 0.81 s to 1.01 s and 1.32 s, respectively.

While DN-Chord performs acceptably, it clearly does not attain the published figures for the MIT implementation (at least 99.9% consistency for a session time of 47 min). Ultimately, the system evaluation rests on an assessment of the ideal tradeoff between code size and performance. It may be the case that churn performance can be at the expense of additional rules that implements lookup retries on a per-hop basis, and better failure detection techniques with adaptive timers.

6.5 SUMMARY

This chapter demonstrates the use of NDlog for expressing two complex overlay networks, namely the Narada mesh formation and a full-fledged implementation of the Chord distributed hash table in 16 and 48 rules, respectively.

The DN-Chord implementation is roughly two orders of magnitude less code than the original C++ implementation. This is a quantitative difference that is sufficiently large that it becomes qualitative: declarative programs that are a few dozen lines of code are markedly easier to understand, debug and extend than multi-thousand-line imperative programs.
One of the promises of a declarative approach to networking is that it can enable automatic optimizations of protocols, much as relational databases can automatically optimize queries. This not only reduces the burden on programmers, it also enables what Codd called data independence [Codd, 1970]: the ability for the implementation of a program to adapt to different underlying execution substrates.

The main goals in this chapter are to demonstrate that the declarative approach is amenable to automatic query optimization, and to illustrate the close connection between network optimization and query optimization. In doing so, this opens up what appears to be a rich new set of research opportunities.

The chapter is organized as follows. Section 7.1 explores the application of traditional Datalog optimizations in the declarative networking context. New techniques for multi-query optimizations and cost-based optimizations are proposed in Sections 7.2 and 7.3, respectively. To validate our proposed optimizations, Section 7.4 presents a performance evaluation of the DN engine executing optimized declarative routing queries on the Emulab testbed.

7.1 TRADITIONAL DATALOG OPTIMIZATIONS

Declarative networking applies three traditional Datalog optimization techniques: aggregate selections, magic sets and predicate reordering. The primary focus of optimizations is on declarative routing queries, which are variants of transitive closure queries.

7.1.1 AGGREGATE SELECTIONS

A naïve execution of the Shortest-path program computes all possible paths, even those paths that do not contribute to the eventual shortest paths. This inefficiency can be avoided with an optimization technique known as aggregate selections [Furfaro et al., 2002, Sudarshan and Ramakrishnan, 1991].

Aggregate selections are useful when the running state of a monotonic aggregate function can be used to prune program evaluation. For example, by applying aggregate selections to the Shortest-path program, each node only needs to propagate the current shortest paths for each destination to neighbors. This propagation can be done whenever a shorter path is derived.
A potential problem with this approach is that the propagation of new shortest paths may be unnecessarily aggressive, resulting in wasted communication. As an enhancement, a modified scheme called \textit{periodic aggregate selections}, works by getting each node to buffer up new paths received from neighbors, recomputes any new shortest paths incrementally, and then propagates the new shortest paths periodically. The periodic technique has the potential for reducing network bandwidth consumption, at the expense of increasing convergence time. It is useful for queries whose input tuples tend to arrive over the network in an order that is not positively correlated with the monotonic aggregate, e.g., computing “shortest” paths for metrics that are not correlated with the network delays that dictate the arrival of the tuples during execution.

In addition, aggregate selections are necessary for the termination of some queries. For example, with aggregate selections, even if paths with cycles are permitted, the \textit{Shortest-Path} program will terminate, avoiding cyclic paths of increasing lengths.

\section*{7.1.2 MAGIC SETS AND PREDICATE REORDERING}

The \textit{Shortest-Path} program computes all-pairs shortest paths. This leads to unnecessary overhead when querying for paths between a limited set of sources and/or destinations. This problem can be alleviated by applying two optimization techniques: \textit{magic-sets rewriting} and \textit{predicate reordering}.

\textbf{Magic-Sets Rewriting:} A query rewrite technique called \textit{magic sets rewriting} [Bancilhon et al., 1986, Beeri and Ramakrishnan, 1987] can be used to limit computation to the relevant portion of the network. The Magic Sets method is closely related to methods such as Alexander [Rohmer et al., 1986] and QSQ [Vieille, 1986], all of which are designed to avoid computing facts that do not contribute to the final answer to a recursive query. The proposed processing techniques in Chapter 4 are based on bottom-up (or forward-chaining) evaluation [Ramakrishnan and Sudarshan, 1999] where the bodies of the rules are evaluated to derive the heads. This has the advantage of permitting set-oriented optimizations while avoiding infinite recursive loops, but may result in computing redundant facts not required by the program. For example, even when the \textit{Shortest-Path} program (Figure 2.5 in Chapter 2) specifies \textit{shortestPath}(\texttt{@a,b,Z,P,C}) as the “goal” of the query, naively applying bottom-up evaluation results in the computation of all paths between all pairs of nodes.

The magic sets rewrite avoids these redundant computations and yet retains the two advantages of bottom-up evaluation. The key ideas behind the rewrite include: (1) the introduction of “magic predicates” to represent variable bindings in queries that a top-down search would ask; and (2) the use of “supplementary predicates” to represent how answers are passed from left-to-right in a rule. The rewritten program is still evaluated in a bottom-up fashion, but the additional predicates generated during the rewrite ensure that there are no redundant computations.

The use of magic sets is illustrated in an example: by modifying rule \textit{sp1} from the \textit{Shortest-Path} program, the following program in Figure 7.1 computes only those paths leading to destinations in the \textit{magicDst} table.

Rule \textit{sp1-d} initializes 1-hop paths for destinations whose \textit{magicDst}(\texttt{@D}) is present in the \textit{magicDst} table. Rule \textit{m1} adds a \textit{magicDst}(\texttt{@a}) fact in the \textit{magicDst} table. Intuitively, the set of
#include(sp2,sp3,sp4)
sp1-d path(@S,D,D,P,C) :- magicDst(@D),link(@S,D,C), P = f_init(S,D).

m1 magicDst(@a).
Query shortestPath(@S,a,P,C).

Figure 7.1: Shortest-Path program with magic sets.

magicDst(@D) facts is used as a “magic predicate” or “filter” in the rules defining paths. This ensures that rule sp2 propagates paths to selected destinations based on the magicDst table (in this case, paths to only node a). The shortest paths are then computed as before using rules sp3 and sp4.

**Predicate Reordering:** The use of magic sets in the previous program is not useful for pruning paths from sources. This is because paths are derived in a "Bottom-Up" (BU) fashion starting from destination nodes, where the derived paths are shipped “backwards” along neighbor links from destinations to sources. Interestingly, switching the search strategy can be done simply by reordering the path and link predicates. Recall from Chapter 2 that predicates in a rule are evaluated in a default left-to-right order. This has the effect of turning sp2 from a right-recursive to a left-recursive rule: the recursive predicate is now to the left of the non-recursive predicate in the rule body. Together with the use of magic sets, the Magic-Shortest-Path program in Figure 7.2 allows filtering on both sources and destinations.

sp1-sd pathDst(S,@D,D,P,C) :- magicSrc(@S), link(@S,D,C),
P = f_init(S,D).

sp2-sd pathDst(S,@D,Z,P,C) :- pathDst(S,@Z,Z1,P1,C1),link(@Z,D,C2),
C = C1 + C2, P = f_concatPath(P1,D).

sp3-sd spCost(@D,S,MIN < C >) :- magicDst(@D),pathDst(S,@D,Z,P,C).
sp4-sd shortestPath(S,@D,P,C) :- spCost(S,@D,C),pathDst(S,@D,Z,P,C).

Figure 7.2: Magic-Shortest-Path program.

The left-recursive Shortest-Path program computes 1-hop paths starting from each magicSrc using rule sp1-sd. Rule sp2-sd then recursively computes new paths by following all reachable links, and stores these paths as pathDst tuples at each destination. Rules sp3-sd and sp4-sd then filter relevant paths based on magicDst, and compute the shortest paths, which can then be propagated along the shortest paths back to the source node. In fact, executing the program in this “Top-Down” (TD) fashion resembles a network protocol called dynamic source routing (DSR) [Johnson and Maltz, 1996] presented in Section 5.3.4 as a declarative routing example program. DSR is proposed for ad-hoc wireless environments, where the high rate of change in the network makes such targeted path discovery more efficient compared to computing all-pairs shortest paths.

Interestingly, the use of magic sets and predicate reordering reveals close connections between query optimizations and network optimizations. By specifying routing protocols in NDlog at a high
level, the two well-known protocols—one for wired networks and one for wireless—differ only in applying a standard query optimization: the order of two predicates in a single rule body. In addition, the use of magic sets allows us to do a more targeted path discovery suited in the wireless setting. Ultimately, such connections between query optimizations and network optimizations will provide a better understanding of the design space of routing protocols.

7.2 MULTI-QUERY OPTIMIZATIONS

In a distributed setting, it is likely that many related queries will be concurrently executed independently by different nodes. A key requirement for scalability is the ability to share common query computations (e.g., pairwise shortest paths) among a potentially large number of queries. Two basic strategies for multi-query sharing in this environment are used: query-result caching and opportunistic message sharing.

Query-Result Caching. Consider the Magic-Shortest-Path program where node $a$ computes $\text{shortestPath}(\emptyset, a, [a, b, d], 6)$ to node $d$. This cached value can be reused by all queries for destination $d$ that pass through $a$, e.g., the path from $e$ to $d$. Currently, our implementation generates the cache internally, building a cache of all the query results (in this case shortestPath tuples) as they are sent back on the reverse path to the source node. Since the subpaths of shortest paths are optimal, these can also be cached as an enhancement.

Opportunistic Message Sharing. In the previous example, different nodes (src/dst) could share their work in running the same program logic with different constants. Sharing across different queries is a more difficult problem, since it is non-trivial to detect query containment in general [Calvanese et al., 2003]. However, in many cases, there can be correlation in the message patterns even for different queries. One example arises when different queries request “shortest” paths based on different metrics, such as latency, reliability and bandwidth; path tuples being propagated for these separate queries may be identical modulo the metric attribute being optimized.

In opportunistic message sharing, multiple outgoing tuples that share common attribute values are essentially joined into one tuple if they are outbound to the same destination; they are re-partitioned at the receiving end. In order to improve the odds of achieving this sharing, outbound tuples may be buffered for a time and combined in batch before being sent.

As an alternative to this opportunistic sharing at the network level, one can achieve explicit sharing at a logical level, e.g., using correlated aggregate selections for pruning different paths based on a combination of metrics. For example, consider running two queries: one that computes shortest latency paths, and another that computes max-bandwidth paths. These programs can be rewritten into a single NDlog program that checks two aggregate selections, i.e., only prune paths that satisfy both aggregate selections.
Currently, rules are expressed using a left-recursive (BU) or right-recursive (TD) syntax (Section 7.1.2). The main goal during query execution is network efficiency (i.e., reducing the burden on the underlying network), which, typically, also implies faster query convergence. It is not difficult to see that neither BU nor TD execution is universally superior under different network/query settings. Even in the simple case of a shortest-path discovery query \texttt{shortestPath(@S,@D,P,C)} between two given nodes \((@S,@D)\), minimizing message overhead implies that the query processor should prefer a strategy that restricts execution to “sparser” regions of the network (e.g., doing a TD exploration from a sparsely-connected source \(@S\)).

Cost-based query optimization techniques are needed to guarantee effective query execution plans. While such techniques have long been studied in the context of relational database systems, optimizing distributed recursive queries for network efficiency raises several novel challenges. The remainder of this section briefly discusses proposed ideas in this area and their ties with work in network protocols.

The Neighborhood Function Statistic. As with traditional query optimization, cost-based techniques must rely on appropriate statistics for the underlying execution environment that can drive the optimizer’s choices. One such key statistic for network efficiency is the local neighborhood density \(N()\). Formally, \(N(X,r)\) is the number of distinct network nodes within \(r\) hops of node \(X\). The neighborhood function is a natural generalization of the size of the transitive closure (i.e., reachability set) of a node, that can be estimated locally (e.g., through other recursive queries running in the background/periodically). \(N(X,r)\) can also be efficiently approximated through approximate-counting techniques using small (log-size) messages [Palmer et al., 2002]. To see the relevance of \(N()\) for the query-optimization problem, consider the example \texttt{shortestPath(@S,@D,P,C)} query, and let \(\text{dist}(s,d)\) denote the distance of \(s, d\) in the network. A TD search would explore the network starting from node \(s\), and (modulo network batching) result in a total of \(N(s, \text{dist}(s,d))\) messages (since it reaches all nodes within a radius of \(\text{dist}(s,d)\) from \(s\)). Note that each node only forwards the query message once, even though it may receive it along multiple paths. Similarly, the cost for a BU query execution is \(N(d, \text{dist}(s,d))\). However, neither of these strategies is necessarily optimal in terms of message cost. The optimal strategy is actually a hybrid scheme that “splits” the search radius \(\text{dist}(s,d)\) between \(s\) and \(d\) to minimize the overall messages; that is, it first finds \(r_s\) and \(r_d\) such that:

\[
(r_s, r_d) = \arg \min_{r_s + r_d = \text{dist}(s,d)} \{ N(s, r_s) + N(d, r_d) \}.
\]

and then runs concurrent TD and BU searches from nodes \(s\) and \(d\) (with radii \(r_s\) and \(r_d\), respectively). At the end of this process, both the TD and the BU search have intersected in at least one network node, which can easily assemble the shortest \((s, d)\) path. While the above optimization problem is trivially solvable in \(O(\text{dist}(s, d))\) time, generalizing this hybrid-rewrite scheme to the case of multiple sources and destinations raises difficult algorithmic challenges. And, of course, adapting such cost-based optimization algorithms to work in the distributed, dynamic setting poses system chal-
Adaptive Network Routing Protocols. As further illustrations on the close connection between networking routing and query optimizations, the networking literature has considered adaptive routing protocols that strongly resemble the use of hybrid rewrites; hence, this is an important area for future investigation and generalization. One interesting example is the class of Zone-Routing Protocols (ZRP) [Haas, 1997]. A ZRP algorithm works by each node precomputing \( k \)-hop-radius shortest paths to neighboring nodes (in its "zone") using a BU strategy. Then, a shortest-path route from a source to destination is computed in a TD fashion, using essentially the Magic-Shortest-Path program described above, utilizing any precomputed shortest paths along the way. Each node sets its zone radius \( k \) adaptively based on the density and rate of change of links in its neighborhood; in fact, recent work [Ramasubramanian et al., 2003] on adjusting the zone radius for ZRP-like routing uses exactly the neighborhood-function statistic.

7.4 EVALUATION OF OPTIMIZATIONS

This section examines the effectiveness of the optimizations that are proposed in this chapter. The workload is primarily based on declarative routing protocols executed using P2 [P2], and measure four variants of the same Shortest-Path program, differing in the link metric each seeks to minimize. Our experimental setup is similar to Section 5.6, where the Shortest-Path program is executed on an overlay network in which each node has four neighbors. In addition, for each neighbor link, we generate additional metrics that include reliability, and a randomly generated value. Note that the reliability metric for each link is synthetically generated to be correlated with latency.

On all the graphs, these queries are labeled by their link metric: Hop-Count, Latency, Reliability and Random, respectively. Recall from Section 5.6.2 that Random serves as the stress case: it is expected to have the worst performance among the different metrics. This is due to aggregate selections being less effective when the aggregate metric is uncorrelated with the network latency.

7.4.1 AGGREGATE SELECTIONS

In order to investigate the effectiveness of aggregate selections for different queries, Figure 7.3 shows the per-node bandwidth usage against time for the Shortest-Path program on all four metrics. Figure 7.4 shows the percentage of eventual best paths completed against time. The results show that Hop-Count has the fastest convergence time of 2.9 s, followed by Latency and Reliability in 3.5 s, and 3.9 s, respectively. Random has the worst convergence time of 5.5 s.

During program execution, the communication overhead incurred by all four queries shows a similar trend (Figure 7.3). Initially, the communication overhead increases as more and more paths (of increasing length) are derived. After it peaks at around \( 53K \text{ Bps} \) per-node, the communication overhead decreases, as fewer and fewer optimal paths are left to be derived. In terms of aggregate communication overhead, Random incurs the most overhead (18.2 MB), while Hop-Count, Latency
7.4. EVALUATION OF OPTIMIZATIONS

The results in Figures 7.5 and 7.6 illustrate the effectiveness of the *periodic aggregate selections* approach, as described in Section 7.1.1, where the wait period is set to 500 ms. In particular, this approach reduces the bandwidth usage of *Hop-Count, Latency, Reliability* and *Random* by 19%, and *Reliability* use 9.1 MB, 12.0 MB and 12.8 MB, respectively. The relatively poor performance of *Random* is due to the lack of correlation between the metric and network latency, leading to a greater tendency for out-of-order arrival of path tuples that results in less effective use of aggregate selection, translating to more messaging overhead and delays.
15%, 23% and 34%, respectively. Random shows the greatest reduction in communication overhead, demonstrating the effectiveness of this technique for improving the performance of queries on metrics that are uncorrelated with network delay.

### 7.4.2 MAGIC SETS AND PREDICATE REORDERING

![Figure 7.7: Aggregate communication overhead (MB) with and without magic sets and caching.](image)

![Figure 7.8: Per-node bandwidth (KBps) for message sharing (300 ms delay).](image)

The next experiment studies the effectiveness of combining the use of magic sets and predicate reordering for lowering communication overhead when the requested shortest paths are constrained by randomly chosen sources and destinations. The workload consists of queries that request source-to-destination paths based on the Hop-Count metric. Each query executes the Magic-Shortest-Path program (Section 7.1.2).

Figure 7.7 shows the aggregate communication overhead as the number of queries increases. The No-MS line represents our baseline, and shows the communication overhead in the absence of rewrites (this essentially reduces to computing all-pairs least-hop-count). The MS line shows the communication overhead when running the program optimized with magic sets, but without any sharing across queries. When there are few queries, the communication overhead of MS is significantly lower than that of NO-MS. As the number of queries increases, the communication overhead of MS increases linearly, exceeding No-MS after 170 queries.

In addition, Figure 7.7 also illustrates the effectiveness of caching (Section 7.2). The MSC line shows the aggregate communication overhead for magic sets with caching. For fewer than 170 queries, there is some overhead associated with caching. This is due to false positive cache hits, where a cache result does not contribute to computing the eventual shortest path. However, as the number of queries increases, the overall cache hit rate improves, resulting in a dramatic reduction of bandwidth. When limiting the choice of destination nodes to 30% (MSC-30%) and 10% (MSC-
The communication overhead levels of at 1.8 MB, and 1 MB, respectively. The smaller the set of requested destinations, the higher the cache hit rate, and the greater the opportunity for sharing across different queries.

### 7.4.3 OPPORTUNISTIC MESSAGE SHARING

The next experiment studies the impact of performing opportunistic message sharing across concurrent queries that have some correlation in the messages being sent. Figure 7.8 shows per-node bandwidth usage for running the queries on different metrics concurrently. To facilitate sharing, each outbound tuple is delayed by 500 ms in anticipation of possible sharing opportunities. The *Latency*, *Reliability* and *Random* lines show the bandwidth usage of each query individually. The *No-Share* line shows the total aggregate bandwidth of these three queries without sharing. The *Share* line shows the aggregate bandwidth usage with sharing. The results clearly demonstrate the potential effectiveness of message sharing, which reduces the peak of the per-node communication overhead from 46 KBps to 31 KBps, and the total communication overhead by 39%.

### 7.4.4 SUMMARY OF OPTIMIZATIONS

The evaluation results are summarized as follows.

1. The aggregate selections optimization indeed reduces communication overhead. Using *periodic aggregate selections* reduces this overhead further.

2. The use of magic sets and predicate reordering reduces communication overhead when only a limited number of paths are queried.

3. Multi-query sharing techniques such as reusing previously computed results and opportunistic result caching demonstrate the potential to reduce communication overhead when there are several concurrent queries.

### 7.5 SUMMARY

This chapter applies a variety of query optimizations to declarative networks. The use of traditional query optimizations is explored, and new optimizations motivated by the distributed setting are proposed. The chapter demonstrates that declarative networks are amenable to automatic optimizations, and showed that many of these optimizations can improve the performance of declarative networks substantially. In addition, the effectiveness of several of our optimization techniques are validated on the Emulab testbed.

This chapter reveals surprising relationships between network optimizations and query optimizations, e.g., a wired protocol can be translated to a wireless protocol by applying the standard database optimizations of magic sets rewrite and predicate reordering. This suggests that these protocols are more similar than they are often made out to be. Recent work [Liu et al., 2009a, 2011a] has
leveraged these connections between network optimizations and query optimizations, to propose a declarative framework for adaptive hybrid wireless ad-hoc network routing protocols.
This chapter presents recent advances in declarative networking. In recent years, research in declarative networking has evolved beyond its original roots as a framework for rapid prototyping, towards one that serves as an important bridge connecting formal theories for reasoning about protocol correctness and actual implementations. The ability to bridge this gap is a major step forward compared to traditional approaches in which formal specifications, proof of protocol correctness and implementations are decoupled from one another; this decoupling leads to increased development time, error prone implementations, and tedious debugging.

This chapter is organized as follows. Section 8.1 describes language extensions of declarative networking. Sections 8.2-8.5 present recent work aimed at addressing four significant challenges in distributed systems: generating safe routing implementations (Section 8.2), securing distributed systems (Section 8.3), debugging distributed systems (Section 8.4), and optimizing distributed systems (Section 8.5).

8.1 LANGUAGE EXTENSIONS

In the original NDlog language, predicates are allowed to be declared as soft-state with lifetimes. In the extreme case, event predicates form transient tables which are used as input to rules but are not stored. To support wireless broadcast [Liu et al., 2009a, 2011a, Muthukumar et al., 2009a], we have introduced a broadcast location specifier denoted by @* which causes a tuple to be broadcast to all nodes within wireless range of the node on which the rule is executed. In order to support network functionality composition and code reuse, Composable Virtual Views [Mao et al., 2008] define rule groups that perform a specific functionality when executed together. These extensions offer different levels of declarativity [Mao, 2009] to meet various application demands.

The meaning of a NDlog program is defined to be the behavior and output obtained by running the program through PSN evaluation [Loo et al., 2006, Nigam et al., 2011]. The Dedalus [Alvaro et al., 2009, Hellerstein, 2010] language is similar to NDlog, except its behavior and output is defined in terms of a model-theoretic semantics. Dedalus also allows users to write rules that mutate state.

Dedalus takes base Datalog, and adds an integer timestamp field to every tuple. State update is expressed as locally-stratified recursion through negation. Message delay and re-ordering is captured by requiring all rules to derive non-local tuples at some non-deterministic future timestamp.
Dedalus uses Saccà and Zaniolo’s choice construct [Saccà and Zaniolo, 1990] to model this non-determinism, which manifests itself in multiple stable models [Gelfond and Lifschitz, 1988]—one model for each possible choice of timestamp.

An interesting question is to what extent the behavior and output of the program is “well-behaved.” The CALM Conjecture [Hellerstein, 2010] states that monotonic coordination-free Dedalus programs are eventually consistent, and non-monotonic programs are eventually consistent when instrumented with appropriate coordination. Recently, Ameloot et al. explored Hellerstein’s CALM conjecture using relational transducers [Ameloot et al., 2011]. They proved that monotonic first order queries are exactly the set of queries that can be computed in a coordination-free fashion in their transducer formalism. Their work uses some different assumptions than traditional declarative networking—for example, they assume that all messages sent by a node are multicast to a fixed set of neighbors, whereas NDlog permits arbitrary unicast.

8.2 GENERATING SAFE ROUTING IMPLEMENTATIONS

The Formally Verifiable Routing (FVR) project addresses a long-standing challenge in networking research: bridging the gap between formal routing theories and actual implementations. The application of declarative networking is especially useful here, serving as an intermediary layer between high-level formal specifications of the network design and low-level implementations.

8.2.1 FORMALLY SAFE ROUTING TOOLKIT

The Formally Safe Routing (FSR) toolkit [Wang et al., 2011] attempts to bridge this gap in the context of interdomain routing by unifying research in routing algebras [Griffin and Sobrinho, 2005] with declarative networking to produce provably correct distributed implementations. Specifically, FSR automates the process of analyzing routing configurations expressed in algebra for safety (i.e., convergence) using the Yices SMT solver [Yices], and automatically compiles routing algebra into declarative routing implementations.

To enable an evaluation of protocol dynamics and convergence time, FSR uses an extended routing algebra [Wang et al., 2011] to automatically generate a distributed routing-protocol implementation that matches the policy configuration—avoiding the time-consuming and error-prone task of manually creating an implementation. FSR generates a provably correct translation to a NDlog specification, which is then executed using the RapidNet declarative networking engine.

The choice of NDlog as the basis for FSR is motivated by the following. First, the declarative features of NDlog allow for straightforward translation from the routing algebra to NDlog programs. Second, NDlog enables a variety of routing protocols and overlay networks to be specified in a natural and concise manner. Given that NDlog specifications are orders of magnitude less code than imperative implementations, this makes possible a clean and concise proof (via logical inductions) of the correctness of the generated NDlog programs with regard to safety. The compact specifications also make it easy to incorporate alternative routing mechanisms to the basic path-vector protocol,
as demonstrated in [Wang et al., 2011]. Finally, when compiled and executed, these declarative protocols perform efficiently relative to imperative routing implementations.

A recent prototype demonstration [Ren et al., 2011] shows how FSR can detect problems in an AS's iBGP configuration (using realistic topologies and policies). FSR has also been used to prove sufficient conditions for BGP safety and empirically evaluate protocol dynamics and convergence time.

FSR serves two important communities. For researchers, FSR automates important parts of the design process and provides a common framework for describing, evaluating, and comparing new safety guidelines. For network operators, FSR automates the analysis of internal router (iBGP) and border gateway (eBGP) configurations for safety violations. For both communities, FSR automatically generates realistic protocol implementations to evaluate real network configurations (e.g., to study convergence time) prior to actual deployment.

8.2.2 DECLARATIVE NETWORK VERIFICATION

In addition to the FSR toolkit, theorem proving techniques have been used for verifying declarative networking programs. The DNV (Declarative Network Verification) [Wang et al., 2009] toolkit demonstrates the feasibility of automatically compiling declarative networking programs written in NDlog into formal specifications recognizable by a theorem prover (e.g., PVS [PVS]) for verification. Unlike model checkers, DNV can express properties beyond the temporal properties to which most model-checking techniques are restricted. It also avoids the state exploration problem inherent in model checking. Theorem proving techniques are also sound and complete: once a property is verified, it holds for all instances of the protocol. Moreover, modern theorem provers come with powerful proof engines that support a large portion of automated proof exploration, enabling the proof of non-trivial theorems with relatively modest human effort.

8.3 SECURING DISTRIBUTED SYSTEMS

The Declarative Secure Distributed Systems (DS2) platform provides high-level programming abstractions for implementing secure distributed systems, achieved by unifying declarative networking and logic-based access control specifications [DeTreville, 2002]. DS2 has a wide range of applications, including reconfigurable trust management [Marczak et al., 2009], secure distributed data processing [Marczak et al., 2010], and tunable anonymity [Sherr et al., 2010].

DS2 is motivated in part by the observation that distributed trust management languages share similarities with both data integration languages and the distributed Datalog languages proposed for declarative networking. These languages support the notion of context (location) to identify components (nodes) in distributed systems. The commonalities between these languages indicate that ideas and methods from the database community are also applicable to processing security policies, suggesting the unification of these declarative languages to create an integrated system.

The DS2 system is currently available for download [RapidNet].
8. RECENT ADVANCES IN DECLARATIVE NETWORKING

8.3.1 SECURE NETWORK DATALOG

The Secure Network Datalog (SeNDlog) language [Zhou et al., 2009] unifies NDlog and logic-based languages for access control in distributed systems. SeNDlog enables network routing, information systems, and security policies to be specified and implemented within a common declarative framework. To execute SeNDlog programs, existing distributed recursive query processing techniques have been extended to incorporate secure communication among untrusted nodes.

In SeNDlog, a set of rules and the associated tuples are bounded to reside at a particular node. This is achieved at the top level for each rule (or set of rules), for example by specifying:

```
At N,
  r1 p :- p1, p2, ..., pn.
  r2 p1 :- p2, p3, ..., pn.
```

The above rules \( r1 \) and \( r2 \) are in the context of \( N \), where \( N \) is either a variable or a constant representing the principal where the rules reside. If \( N \) is a variable, it will be instantiated with local information upon rule installation. In a trusted distributed environment, \( N \) simply represents the network address of a node: either a physical address (e.g., an IP address) or a logical address (e.g., an overlay identifier). In a multi-user multi-layered network environment where multiple users and overlay networks may reside on the same physical node, \( N \) can include the user name and an overlay network identifier. This is unlike declarative networking in which location specifiers denote physical IP address.

SeNDlog allows different principals or contexts to communicate via import and export of tuples. The communication serves two purposes: (1) maintenance messages as part of a network protocol’s updates on routing tables, and (2) distributed derivation of security decisions. Imported tuples from a principal \( N \) are automatically quoted using “\( N \text{ says } p \)” to differentiate them from local tuples. During the evaluation of SeNDlog rules, derived tuples are allowed to be communicated among contexts via the use of import predicates and export predicates:

- An import predicate is of the form “\( N \text{ says } p \)” in a rule body, where principal \( N \) asserts the predicate \( p \).
- An export predicate is of the form “\( N \text{ says } p@X \)” in a rule head, where principal \( N \) exports the predicate \( p \) to the context of principal \( X \). Here, \( X \) can be a constant or a variable. If \( X \) is a variable, in order to make bottom-up evaluation efficient, it is further required that the variable \( X \) occur in the rule body. As a shorthand, “\( N \text{ says } p \)” can be omitted if \( N \) is the principal where the rule resides.

By exporting tuples only to specified principals, the use of export predicates ensures confidentiality and prevents information leakage. With the above definitions, a SeNDlog rule is a Datalog rule where the rule body can include import predicates and the rule head can be an export predicate.
To illustrate SeNDlog using an example, consider a secure implementation of the declarative path vector protocol (shown in Figure 8.1). At every node Z, this program takes as input neighbor(Z,X) tuples that contain all neighbors X for Z. The program generates route(Z,X,P) tuples, each of which stores the path P from source Z to destination X. The basic protocol specification is similar to the all-pairs reachable example presented in Section 2.2, with additional predicates for computing the actual path using the f_concat function which prepends neighbor X to the input path P.

The input carryTraffic and acceptRoute tables, respectively, represent the export and import policies of node Z. Each carryTraffic(Z,X,Y) tuple represents the fact that node Z is willing to serve all network traffic on behalf of node X to node Y, and each acceptRoute(Z,Y,X) tuple represents the fact that node Z will accept a route from node X to node Y. A more complex version of this protocol will have additional rules that derive carryTraffic and acceptRoute, avoid path cycles and also derive shortest paths with the least hop count.

The path-vector protocol is used for inter-domain routing over the Internet and is known to be vulnerable to a variety of attacks due to the lack of mechanisms for verifying the authenticity and authorization of routing control traffic. One potential solution is to authenticate every routing control message, as proposed for Secure BGP [S-BGP].

\[\begin{align*}
\text{At Z,} \\
\text{z1 route}(Z,X,P) & : \text{neighbor}(Z,X), P=f_{\text{initPath}}(Z,X). \\
\text{z2 route}(Z,Y,P) & : X \text{ says advertise}(Y,P), \text{acceptRoute}(Z,X,Y). \\
\text{z3 advertise}(Y,P1,X) & : \text{neighbor}(Z,X), \text{route}(Z,Y,P), \\
& \text{carryTraffic}(Z,X,Y), P1=f_{\text{concat}}(X,P).
\end{align*}\]

**Figure 8.1:** SeNDlog specification of the secure path-vector protocol.

In this example program, such authentication can be naturally specified via the use of “says” to ensure that all advertise tuples are verified by the recipients for authenticity. Rule z1 takes as input neighbor(Z,X) tuples, and computes all the single hop route(Z,X,P) containing the path [Z,X] from node Z to X. Rules z2 and z3 compute routes of increasing hop counts. Upon receiving an advertise(Y,P) tuple from X, Z uses rule z2 to decide whether to accept the route advertisement based on its local acceptRoute table. If the route is accepted, a route tuple is derived locally, and this results in the generation of an advertise tuple which is further exported by node Z via rule z3 to some of its neighbors X as determined by the policies stored in the local carryTraffic table.

SeNDlog is able to compactly specify a variety of secure distributed protocols. Zhou et al. [2009] has demonstrated, for example, the use of SeNDlog for performing secure distributed joins and securing distributed hash tables [Balakrishnan et al., 2003].
8. RECENT ADVANCES IN DECLARATIVE NETWORKING

8.3.2 RECONFIGURABLE SECURITY

Although one can achieve a high level of security using a “one-size-fits-all” solution with fixed constructs like `says`, an extensible trust management framework where users can write and reconfigure their own constructs like `says` is applicable to a much broader range of settings. For example, programmers could customize the security protocols used by their application based on the execution environment without modifying the application logic. `LBTrust` [Marczak et al., 2009] extends SeNDlog to support user-defined security constructs that can be customized and composed in a declarative fashion. To validate these ideas in a production system, this extension has been implemented in the LogicBlox [LogicBlox Inc.] system, an emerging commercial Datalog-based platform for enterprise software systems.

In addition, LogicBlox is enhanced to support meta-rules [Condie et al., 2008]—Datalog rules that operate on the rules of the program as input, and produce new rules as output—and meta-constraints—Datalog constraints that restrict the allowable rules in the program. Security constructs are written using these two ingredients. For example, the `says` construct would consist of meta-rules that rewrite the program to perform signing of all exported messages, and constraints that ensure that all imported messages have valid signatures. In LBTrust, a variety of security primitives for authentication, confidentiality, integrity, speaks-for, and restricted delegation can be supported. Based on these primitives, several existing distributed trust management systems (e.g., Binder [DeTreville, 2002], SD3 [Jim, 2001], Delegation Logic [Li et al., 2003], and SeNDlog) can be implemented in LBTrust.

A follow-up to LBTrust is the `SecureBlox` [Marczak et al., 2010] system, which restricts the use of meta-programming to make it a fully static, compile-time operation. SecureBlox includes support for physical distribution, and looks at performance-security tradeoffs between different constructs in distributed systems. Similar to LBTrust, SecureBlox allows meta-programmability for compile-time code generation based on the security requirements and trust policies of the deployed environment.

While security is specifically studied in the LBTrust and SecureBlox work, the general pattern of using meta-programming to decompose a logic program into different aspects representing cross-cutting concerns is more broadly applicable.

8.3.3 APPLICATION-AWARE ANONYMITY

To further illustrate the feasibility of these methods and technologies for the development of secure distributed systems, the Application-Aware Anonymity (A³) system [A³, Sherr et al., 2010] is a distributed peer-to-peer service that provides high-performance anonymity for the masses. A³ uses SeNDlog for implementing an extensible policy engine for customizing its relay selection and instantiation strategies. A³ allows applications to construct anonymous Onion [Goldschlag et al., 1999] paths that adhere to application specific constraints (e.g., end-to-end latency). Unlike existing anonymity systems that construct paths according to predefined criteria, A³ enables applications to specify the requirements of their anonymous paths. For example, anonymized Voice-over-IP services can request paths with low latency and modest bandwidth requirements, while streaming
8.4 DEBUGGING DISTRIBUTED SYSTEMS

In the context of distributed systems, it is very common for system administrators to perform analysis tasks that essentially amount to network provenance [Zhou et al., 2008, 2010] queries. For example, they might ask diagnostic queries to determine the root cause of a malfunction, forensic queries to identify the source of an intrusion, or profiling queries to find the reason for suboptimal performance.

The NetTrails [Zhou et al., 2010, 2011c] system is a declarative platform for incrementally maintaining, interactively navigating, and querying network provenance in a distributed system. During the system execution, NetTrails incrementally maintains provenance information using RapidNet as its distributed query engine. NetTrails offers a unifying framework, as both maintenance and querying functionalities are specified as NDlog programs.

NetTrails consists of two subcomponents: First, a maintenance engine takes as input either NDlog programs or input/output dependencies captured from legacy applications, and then incrementally computes and maintains network provenance information as distributed relational tables. Second, a distributed query engine executes user-customizable provenance queries that are evaluated across multiple nodes. Legacy systems are supported either by modifying the application’s source code to explicitly report provenance, or by using an external specification of the application’s protocol to derive provenance information by observing a node’s inputs and outputs [Zhou et al., 2011b].

8.4.1 NETWORK PROVENANCE MODEL

In NetTrails, the provenance graph is internally maintained as relational tables which are distributed and partitioned across all nodes in the network. Network provenance is modeled as an acyclic graph $G(V, E)$. The vertex set $V$ consists of tuple vertices and rule execution vertices. Each tuple vertex in the graph is either a base tuple or a computation result, and each rule execution vertex represents an instance of a rule execution given a set of input tuples. The edge set $E$ represents dataflows between tuples and rule execution vertices.
To illustrate, consider an example network consisting of three nodes \( a, b \) and \( c \) connected by three bi-directional links \((a, b), (a, c)\) and \((b, c)\) with costs 3, 5 and 2 respectively. The following three-rule MinCost program found in Figure 8.3 computes the minimal path cost between each pair of nodes.

\[
\begin{align*}
\text{sp1: } & \text{pathCost}(S, D, C) :- \text{link}(S, D, C). \\
\text{sp2: } & \text{pathCost}(S, D, C1+C2) :- \text{link}(Z, S, C1), \text{bestPathCost}(Z, D, C2). \\
\text{sp3: } & \text{bestPathCost}(S, D, MIN < C>) :- \text{pathCost}(S, D, C).
\end{align*}
\]

**Figure 8.3:** The MinCost protocol.

Figure 8.2 shows the provenance for a specific derived tuple \( \text{bestPathCost}(a, c, 5) \), based on the dependency logic captured by the MinCost program. For instance, the figure shows that \( \text{bestPathCost}(a, c, 5) \) is generated from rule sp3 at node \( a \) taking \( \text{pathCost}(a, c, 5) \) as the input. To trace further, \( \text{pathCost}(a, c, 5) \) has two derivations: the locally derivable one-hop path \( a \rightarrow c \) and the two-hop path \( a \rightarrow b \rightarrow c \) that requires a distributed join at \( b \).

### 8.4.2 DISTRIBUTED MAINTENANCE AND QUERYING

Given the adoption of a declarative networking engine, data dependencies are explicitly captured in derivation rules.\(^1\) The provenance maintenance in a dynamic system execution can be performed in a straightforward manner: an automatic rule rewrite algorithm takes as input a set of derivation rules, and outputs a modified program that contains additional rules for capturing the provenance information. These additional rules define network provenance in terms of views over base and derived tuples. As the network protocol executes and updates network state, views are incrementally recomputed.

Once generated, network provenance can be queried by issuing distributed queries. Since provenance information is distributed across nodes, query execution performs a traversal of the provenance graphs in a distributed fashion.

NetTrails allows users to customize the provenance queries. For instance, users can query for a tuple’s lineage, the set of nodes that have been involved in the derivation of a given tuples, and/or the total number of alternative derivations. To reduce querying overhead, NetTrails adopts a set of optimization techniques [Zhou et al., 2010], including caching previously queried results, leveraging alternative tree traversal orders, and performing threshold-based pruning.

Figure 8.4 shows an example execution of a demonstration [Zhou et al., 2011c] that highlights the provenance of the system state (captured as tuples) for a running MinCost program. One may further issue customized provenance queries and visually inspect the progressive steps of the distributed querying.

\(^1\)For legacy applications, the data dependencies (reported by the modified source code or inferred from the observed I/Os) can be formulated as derivation rules as well [Zhou et al., 2011b].
8.4. SECURITY AND TEMPORAL EXTENSIONS

NetTrails provides functionality required for richer provenance queries by adding: (i) new provenance models and maintenance strategies for capturing the time, distribution, and causality of updates in distributed systems [Zhou et al., 2011a], and (ii) novel query processing and optimization techniques for efficiently and securely answering queries at scale [Zhou et al., 2011b].

NetTrails explicitly captures causality: if some network state $\alpha$ depends on some other state $\beta$, and $\beta$ is changed, the provenance of the change in $\alpha$ is attributable to the change in $\beta$. Additionally, since one of the potential use cases is forensics, NetTrails achieves strong security guarantees even in the presence of misbehaving and potentially malicious nodes. NetTrails utilizes secure network provenance [Zhou et al., 2011b] to provide the strong guarantee that either a returned provenance query is accurate and complete, or that a misbehaving node is identified with non-repudiable evidence against the node.

To demonstrate the capabilities of NetTrails’s temporal and security extensions, a number of use cases of the NetTrails system have been developed.

- **Network Routing.** The Border Gateway Protocol (BGP) used for interdomain routing over the Internet is plagued by a variety of attacks and malfunctions. NetTrails has been applied to the Quagga BGP daemon [Quagga] and demonstrated how NetTrails enables a network administrator to determine why an entry from a routing table has disappeared. NetTrails is capable of detecting well-known BGP misconfigurations.

- **Distributed Hash Tables.** NetTrails has been applied to a declarative implementation of the Chord [Loo et al., 2005a] distributed hash table; no modifications are required to the Chord
source code. NetTrails has the ability to detect a well-known attack against Chord in which
the attacker gains control over a large fraction of the neighbors of a correct node, and is then
able to drop or reroute messages to this node and prevent correct overlay operation.

- **Hadoop MapReduce.** Finally, NetTrails has been applied to Hadoop MapReduce [Hadoop].
  Hadoop is manually instrumented to report provenance at the level of individual key-value
  pairs. The *WordCount* program written in Hadoop is used to reports the number of occurrences
  of each word in a 1.2 GB Wikipedia dataset. In this scenario, the provenance of a given
  (unlikely) key-value pair in the output is queried. NetTrails revealed that unexpected results
  might be attributed to a faulty or compromised map worker. More generally, NetTrails is able
to identify the causes of suspicious MapReduce outputs.

## 8.5 OPTIMIZING DISTRIBUTED SYSTEMS

In distributed systems management, operators often configure system parameters that optimize
performance objectives, given constraints in the deployment environment. Recent extensions to the
original declarative networking framework has led to a declarative optimization platform that enables
constraint optimization problems (COP) to be declaratively specified and incrementally executed in
distributed systems.

Traditional COP implementation approaches use imperative languages such as C++ or Java and
often result in cumbersome and error-prone programs that are difficult to maintain and customize.
Moreover, due to scalability and management constraints imposed across administrative domains,
it is often necessary to execute COP in a distributed setting in which multiple local solvers must
coordinate with one another. Each local solver handles a portion of the whole problem, and they
together achieve a global objective.

Central to the optimization platform is the integration of a declarative networking engine [Loo et al., 2009] with an off-the-shelf constraint solver [Gecode]. This platform has been
applied to two use cases.

### 8.5.1 USE CASES: PUMA AND COPE

First, the *Policy-based Unified Multi-radio Architecture* (PUMA), a declarative constraint solving
platform for optimizing wireless mesh networks. In PUMA, network operators can flexibly vary the
choice of routing via adaptable hybrid routing protocols [Liu et al., 2011a]. The hybrid technique
combines several existing protocols (e.g., proactive, reactive, and epidemic) with specific criteria
for determining when particular protocols are to be used. The hybrid compositional capabilities
are particularly useful for routing in heterogeneous network settings in which application needs
and network conditions keep changing over time. In addition, PUMA enables policies for wireless
channel selection [Liu et al., 2012] to be declaratively specified and optimized; such policies may
reduce network interference and maximize throughput while not violating constraints (for instance,
refraining from channels owned exclusively by the primary users [Perich, 2007]).
Second, the *Cloud Orchestration Policy Engine* (COPE) [Liu et al., 2011b] uses the optimization framework to declaratively control the provisioning, configuration, management and decommissioning of cloud resource orchestration. COPE enables the automatic realization of customer service level agreements while simultaneously conforming to operational objectives of the cloud providers.

Beyond these two use cases, this platform has a wide-range of potential applications, including optimizing distributed systems for load balancing, robust routing, scheduling, and security.

### 8.5.2 COLOG LANGUAGE AND COMPILATION

The optimization platform uses the *Colog* declarative policy language. Colog allows operators to concisely model distributed system resources and formulate management decisions as declarative programs with specified goals and constraints. Compared to traditional imperative alternatives, Colog results in code that is smaller by orders of magnitude, and is easier to understand, debug and extend. Here, high-level intuitions of Colog are presented; a more comprehensive treatment of the language can be found here [Liu et al., 2011b, 2012].

- **Language extensions.** Based on NDlog, Colog extends traditional NDlog with constructs for expressing goals and constraints. Two reserved keywords—`goal` and `var`, respectively, specify the optimization goal and variables used by the constraint solver. Constraint rules of the form $F_1 \rightarrow F_2, F_3, \ldots, F_n$ denote that whenever $F_1$ is true, then the rule body ($F_2$ and $F_3$ and $\ldots$ and $F_n$) must also be true to satisfy the constraint. Unlike a Datalog rule which derives new values for a predicate, a constraint restricts a predicate’s allowed values, hence representing an invariant that must be maintained at all times. These are used by the solver to limit the search space when computing the optimization goal. Using Colog, it is easy to customize policies simply by modifying the goals and constraints, and by adding additional derivation rules.

- **Distributed COP.** Colog is extended for execution in a distributed setting. At a high level, multiple solver nodes execute a local COP, and then iteratively exchange COP results with neighboring nodes until a stopping condition is reached. Similar to NDlog, in the distributed COP program, a location specifier `@` denotes the source location of each corresponding tuple. This allows us to write rules in which the input data span multiple nodes—a convenient language construct for formulating distributed optimizations.

One of the interesting aspects of Colog, from a query processing standpoint, is the integration of RapidNet (an incremental bottom-up distributed Datalog evaluation engine) and Gecode (a top-down goal-oriented constraint solver). This integration allows us to implement a distributed solver that can perform incremental and distributed constraint optimizations.

To execute distributed COP rules, Colog uses RapidNet, which already provides a runtime environment for implementing these rules. At a high level, each distributed rule or constraint (with multiple distinct location specifiers) is rewritten using a localization rewrite [Loo et al., 2009] step. This transformation results in rule bodies that can be executed locally and rule heads that can be
derived and sent across nodes. The beauty of this rewrite is that even if the original program expresses distributed properties and constraints, the rewrite process will realize multiple local COP operations at different nodes, and have the output of COP operations via derivations sent across nodes.

8.6 SUMMARY

This chapter focuses on the use of declarative networking for addressing four main challenges in the distributed systems development cycle: the generation of safe routing implementations, debugging, security and privacy, and optimizing distributed systems. In addition to the fast-prototyping capabilities brought by the orders of magnitude reduction in code size (compared to imperative implementation), recent advances explore the research opportunities enabled by the root of declarative networking in logic-based specification languages. It fundamentally eases the process of bridging formal analysis and implementation in practice, to allow automatic code-synthesis for provably correct implementation. In addition, the execution model of NDlog aligns naturally with how distributed systems execute in general, enabling an automated approach towards maintaining and querying state dependencies using network provenance.
In Jim Gray’s Turing Award Lecture [Gray, 2000], one of his grand challenges was the development of “automatic programming” techniques that would be: (a) 1000 times easier for people to use, (b) directly compiled into working code, and (c) suitable for general purpose use. Butler Lampson reiterated the first two points in a subsequent invited article, but suggested that they might be more tractable in domain-specific settings [Lampson, 2003].

Declarative Networking has gone a long way towards Gray’s vision, if only in the domain of network protocol implementation. On multiple occasions we have seen at least two orders of magnitude reduction in code size, with the reduced linecount producing qualitative improvements. In the case of Chord, a multi-thousand line C++ library was rewritten as a declarative program that fits on a single sheet of paper—a software artifact that can be studied and holistically understood by a programmer in a single sitting.

A high-level declarative language not only simplifies a programmer’s work, but re-focuses the programming task on appropriately high-level issues. For example, declarative routing has demonstrated that discussions of routing in wired vs. wireless networks should not result in different protocols, but rather in different compiler optimizations for the same simple declaration, with the potential to be automatically blended into new hybrid strategies as networks become more diverse [Chu and Hellerstein, 2009, Liu et al., 2009a, Loo et al., 2005b]. This lifting of abstractions seems well suited to the increasing complexity of modern networking, introducing software malleability by minimizing the affordances for over-engineering solutions to specific settings.

Broadly, declarative networking have impacted the networking and database communities in the following ways. For the networking community, declarative networking has the potential to fundamentally alter the way networking protocols are designed, implemented and verified. For the database community, this research agenda has been a factor towards rekindling interest in recursive query research [Huang et al., 2011], and highlighting research opportunities at the intersection of data management and networking, and synergies available by intertwining the two within a single declarative framework.
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Authors’ Biographies

BOON THAU LOO

Boon Thau Loo is an Assistant Professor in the Computer and Information Science department at the University of Pennsylvania. He received his Ph.D. degree in Computer Science from the University of California at Berkeley in 2006. Prior to his Ph.D., he received his M.S. degree from Stanford University in 2000, and his B.S. degree with highest honors from UC Berkeley in 1999. His research focuses on distributed data management systems, Internet-scale query processing, and the application of data-centric techniques and formal methods to the design, analysis and implementation of networked systems.

WENCHAO ZHOU

Wenchao Zhou is a Ph.D. student in the Computer and Information Science department at the University of Pennsylvania. He received his B.S. degree from Tsinghua University in 2006 and M.S. Degree from the University of Pennsylvania in 2009. His research interests are in distributed systems, focusing on logic-based declarative approach for verifiable secure distributed systems, and the application of data-centric techniques to secure forensics and diagnosis in potentially adversarial environments.