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## **Keywords**

Bisimulation, open maps, dynamical systems, control systems, hybrid systems

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# Bisimulation relations for dynamical, control, and hybrid systems

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## Abstract

The fundamental notion of bisimulation equivalence for concurrent processes, has escaped the world of continuous, and subsequently, hybrid systems. Inspired by the categorical framework of Joyal, Nielsen and Winskel, we develop novel notions of bisimulation equivalence for dynamical systems as well as control systems. We prove that this notion can be captured by the abstract notion of bisimulation as developed by Joyal, Nielsen and Winskel. This is the first unified notion of system equivalence that transcends discrete and continuous systems. Furthermore, this enables the development of a novel and natural notion of bisimulation for hybrid systems, which is the final goal of this paper. This completes our program of unifying bisimulation notions for discrete, continuous and hybrid systems.

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## 1 Introduction

Bisimulation is a notion of system equivalence that has become one of the primary tools in the analysis of concurrent processes. When two concurrent

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systems are bisimilar, known properties are readily transferred from one system to the other. For every notion of concurrency or process algebra, there has been a different notion of bisimulation and frequently several competing notions.

In [10], Joyal, Nielsen and Winskel proposed the notion of *span of open maps* in an attempt to understand the various equivalence notions for concurrency in an abstract categorical setting. They also showed that this abstract definition of bisimilarity captures the strong bisimulation relation of Milner [17]. Subsequently in [5] it was shown that abstract bisimilarity can also capture Hennessy's testing equivalences [7], Milner and Sangiorgi's barbed bisimulation [18] and Larsen and Skou's probabilistic bisimulation [14]. More recently, in [2], a bisimulation relation for Markov processes on Polish spaces was formulated in this categorical framework, extending the work of Larsen and Skou. Other attempts to formulate the notion of bisimulation in categorical language, include the coalgebraic approach of [9,21]. We will further discuss these methods in Section 7 where we compare our approach to those in the literature.

Despite the plethora of bisimulation notions in concurrency, the notion of bisimulation have escaped the world of continuous and dynamical systems, as noted in [26,25]. Furthermore, the lack of bisimulation notions for continuous systems has impeded developing bisimulation equivalence for hybrid systems. Inspired by the abstract framework in [10], in this paper we transcend from the discrete to the continuous world and develop novel notions of bisimulation equivalence for dynamical systems, control systems, and subsequently hybrid systems.

Despite the existence of traditional notions of equivalence in dynamical systems and control theory [11], the notion of bisimulation offers two novelties even in the more traditional setting of continuous systems. Dynamical systems are deterministic systems for which bisimulation equivalence is equivalent to trajectory equivalence. For control systems, however, one can think of the control input as producing nondeterministic system behavior, and therefore bisimulation equivalence is a finer notion of equivalence for nondeterministic dynamical systems than trajectory equivalence. Furthermore, system equivalence by bisimulation relation is a notion of equivalence that does not require control systems to be of minimal dimension or even of the same dimension.

There has been very recent work characterizing the the notion of bisimulation for dynamical and control systems in a functional setting, that is the bisimulation relation is a functional relation [19,24]. In [6], we have extended this notion to relational setting and further have shown that this equivalence relation is captured by the abstract bisimulation relation of [10]. In this paper, we also develop novel and natural notions of bisimulation for hybrid systems, and to show that this notion is also captured in the framework of [10]. In

addition to providing novel notions of system equivalence for dynamical and control systems, unifying the notion of bisimulation across discrete and continuous domains, our results also extend the applicability of the categorical framework to the domain of hybrid dynamical systems. This completes our program of unifying bisimulation notions for discrete, continuous, and hybrid systems.

The rest of the paper is organized as follows: In Section 2, we briefly review the abstract formulation of the notion of bisimilarity as developed in [10]. Section 3 provides the main application of this method in concurrency theory and recalls that the abstract bisimilarity captures Milner’s strong bisimulation relation. Section 4 reviews our recently developed notions of bisimulation for dynamical systems and Section 5 does the same for control systems. The main results of the paper are contained in Section 6 where we introduce and discuss bisimulation relations for hybrid systems. Section 7 briefly reviews the coalgebraic approach to bisimulation and discusses the reasons for our choice of working within the framework of [10]. We also review some other categorical approaches to the modelling of hybrid systems and compare those to our models. Finally in Section 8 we conclude our study while presenting some future research direction. Given that the sections on dynamical, control and hybrid systems use definitions and facts from differential geometry, we have included an appendix that reviews as much of this background material as we need to develop our work.

## 2 Bisimulation and open maps

The notion of bisimilarity, as defined in [17], has turned out to be one of the most fundamental notions of operational equivalences in the field of process algebras. This has inspired a great amount of research on various notions of bisimulation for a variety of concurrency models. In order to unify most of these notions, Joyal, Nielson and Winskel gave in [10] an abstract formulation of bisimulation in a category theoretical setting.

The approach of [10] introduces a category of models where the objects are the systems in question, and the morphisms are simulations. More precisely, it consists of the following components:

- **Model Category:** The category  $\mathbf{M}$  of *models* with objects the systems being studied, and morphisms  $f : X \rightarrow Y$  in  $\mathbf{M}$ , that should be thought of as a simulation of system  $X$  in system  $Y$ .
- **Path Category:** The category  $\mathbf{P}$ , called *the path category*, where  $\mathbf{P}$  is a subcategory of the category  $\mathbf{M}$  of path objects, with morphisms expressing how they can be extended.

The path category will serve as an abstract notion of time. Since the path category  $\mathbf{P}$  is a subcategory of the category  $\mathbf{M}$  of models, time is thus modeled as a (possibly trivial) system within the same category  $\mathbf{M}$  of models. This allows the unification of notions of time across discrete and continuous domains.

**Definition 1** A *path* or *trajectory* in an object  $X$  of  $\mathbf{M}$  is a morphism  $p : P \rightarrow X$  in  $\mathbf{M}$  where  $P$  is an object in  $\mathbf{P}$ .

Let  $f : X \rightarrow Y$  be a morphism in  $\mathbf{M}$ , and  $p : P \rightarrow X$  be a path in  $X$ , then clearly  $f \circ p : P \rightarrow Y$  is a path in  $Y$ . Note that a path is a morphism in  $\mathbf{M}$  and so is the map  $f$  and hence  $f \circ p$  is a map in  $\mathbf{M}$ . This is the sense in which  $Y$  *simulates*  $X$ ; any path (trajectory)  $p$  in  $X$  is matched by the path  $f \circ p$  in  $Y$ .

The abstract notion of bisimulation in [10] demands a slightly stronger version of simulation as follows: Let  $m : P \rightarrow Q$  be a morphism in  $\mathbf{P}$  and let the diagram

$$\begin{array}{ccc} P & \xrightarrow{p} & X \\ m \downarrow & & \downarrow f \\ Q & \xrightarrow{q} & Y \end{array}$$

commute in  $\mathbf{M}$ , i.e., the path  $f \circ p$  in  $Y$  can be extended via  $m$  to a path  $q$  in  $Y$ . Then we require that there exist  $r : Q \rightarrow X$  such that in the diagram

$$\begin{array}{ccc} P & \xrightarrow{p} & X \\ m \downarrow & \nearrow r & \downarrow f \\ Q & \xrightarrow{q} & Y \end{array}$$

both triangles commute. Note that this means that the path  $p$  can be extended via  $m$  to a path  $r$  in  $X$  which matches  $q$ . In this case, we say that  $f : X \rightarrow Y$  is  $\mathbf{P}$ -open. It can be shown that  $\mathbf{P}$ -open maps form a subcategory of  $\mathbf{M}$ .

**Proposition 2** Let  $\mathbf{M}$  be a category and  $\mathbf{P}$  be the subcategory of path objects. Then,  $\mathbf{P}$ -open maps in  $\mathbf{M}$  form a subcategory of  $\mathbf{M}$ .

**PROOF.** Let  $X$  be an object in  $\mathbf{M}$ , we first show that  $id_X : X \rightarrow X$  is a  $\mathbf{P}$ -open map. Let  $p : P \rightarrow X$  and  $q : Q \rightarrow X$  and  $m : P \rightarrow Q$ , where  $P$  and  $Q$  are path objects in  $\mathbf{P}$ . Assume also that  $id_X p = qm$ . Then let  $r = q : Q \rightarrow X$ :  $id_X r = id_X q = q$  and  $qm = p$ . Now suppose,  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$  are  $\mathbf{P}$ -open maps, let  $p : P \rightarrow X$  and  $q : Q \rightarrow Z$ , and  $m : P \rightarrow Q$ . Also assume that  $(gf)p = qm$ . As  $g : Y \rightarrow Z$  is a  $\mathbf{P}$ -open map then there exists an

$r : Q \rightarrow Y$  such that the triangles in the following diagram commute:

$$\begin{array}{ccc} P & \xrightarrow{f \circ p} & Y \\ m \downarrow & \nearrow r & \downarrow g \\ Q & \xrightarrow{q} & Z \end{array}$$

and as  $f : X \rightarrow Y$  is  $\mathbf{P}$ -open, there exists a map  $s : Q \rightarrow X$  making the triangles in the following diagram commute:

$$\begin{array}{ccc} P & \xrightarrow{p} & X \\ m \downarrow & \nearrow s & \downarrow f \\ Q & \xrightarrow{r} & Y \end{array}$$

Now  $(gf)s = g(fs) = gr = q$ , using the second and the first diagrams for the last two equalities respectively. Also  $sm = p$  from the second diagram above.

□

The definition of  $\mathbf{P}$ -open maps leads to the notion of  $\mathbf{P}$ -bisimilarity. We say that objects  $X_1$  and  $X_2$  of  $\mathbf{M}$  are  $\mathbf{P}$ -bisimilar, denoted  $X_1 \sim_{\mathbf{P}} X_2$  iff there is a span of  $\mathbf{P}$ -open maps  $(X, f_1, f_2)$  as shown below:

$$\begin{array}{ccc} & X & \\ f_1 \swarrow & & \searrow f_2 \\ X_1 & & X_2 \end{array}$$

The relation of  $\mathbf{P}$ -bisimilarity between objects is clearly reflexive (identities are  $\mathbf{P}$ -open) and symmetric. It is also transitive *provided the model category  $\mathbf{M}$  has pullbacks*, due to the fact that pullbacks of  $\mathbf{P}$ -open morphisms are  $\mathbf{P}$ -open (see [10] for a proof). Indeed suppose  $X_1 \sim_{\mathbf{P}} X_2$  and  $X_2 \sim_{\mathbf{P}} X_3$ , then  $X_1 \sim_{\mathbf{P}} X_3$  as can be seen from the following diagram.

$$\begin{array}{ccccc} & & Y & & \\ & & g'_1 \swarrow & & \searrow f'_2 \\ & & X & & X' \\ f_1 \swarrow & & & & \swarrow g_1 \\ X_1 & & & & X_2 & & X_3 \\ & & \searrow f_2 & & \searrow g_2 \end{array}$$

Note that given  $X_1$  and  $X_2$  in  $\mathbf{M}$ , if there exists a  $\mathbf{P}$ -open morphism  $f : X_1 \rightarrow X_2$ , or a  $\mathbf{P}$ -open morphism  $g : X_2 \rightarrow X_1$ , then  $X_1$  and  $X_2$  are  $\mathbf{P}$ -bisimilar.

The spans are  $(X_1, id_{X_1}, f)$  and  $(X_2, g, id_{X_2})$  respectively.

Not all model categories that we consider have pullbacks of all morphisms. In particular the category of smooth manifolds and smooth mappings does not have pullbacks of *all* morphisms. We discuss the solution to this problem in the sections below.

### 3 Labelled Transition Systems

We briefly recall the definitions and results in [10] for labelled transition systems. We will also refer to these definitions and results later, when we discuss hybrid dynamical systems.

**Definition 3** A *labelled transition system*  $T = (S, i, L, \rightarrow)$  consists of the following:

- A set  $S$  of states with a distinguished state  $i \in S$  called the *initial state*.
- A set  $L$  of labels
- A ternary relation  $\rightarrow \subseteq S \times L \times S$

The model category  $\mathbf{T}$ , of transition systems has labelled transition systems as objects and a morphism  $f : T_1 \rightarrow T_2$  with  $T_1 = (S_1, i_1, L_1, \rightarrow_1)$  and  $T_2 = (S_2, i_2, L_2, \rightarrow_2)$  is given by  $f = (\sigma, \lambda)$  where  $\sigma : S_1 \rightarrow S_2$  with  $\sigma(i_1) = i_2$  and  $\lambda : L_1 \rightarrow L_2$  is a partial function such that

- (1)  $(s, a, s') \in \rightarrow_1$  and  $\lambda(a)$  defined, implies  $(\sigma(s), \lambda(a), \sigma(s')) \in \rightarrow_2$  and
- (2)  $(s, a, s') \in \rightarrow_1$  and  $\lambda(a)$  undefined, implies  $\sigma(s) = \sigma(s')$ .

In order to discuss the usual bisimilarity of transition systems we need to restrict our model category to the subcategory  $\mathbf{T}_L$  of transition systems with the same label set  $L$  and morphisms of the form  $f = (\sigma, id_L)$  which preserve all the labels. The category  $\mathbf{T}_L$  has both binary products and pullbacks [10].

**Definition 4** Given transition systems  $T_1 = (S_1, i_1, L, \rightarrow_1)$  and  $T_2 = (S_2, i_2, L, \rightarrow_2)$  in  $\mathbf{T}_L$  we define their product  $T = (S, i, L, \rightarrow)$  as follows:

- $S = S_1 \times S_2$  with projections  $\rho_1$  and  $\rho_2$ ,
- $i = (i_1, i_2)$ ,
- $((s_1, s_2), a, (s'_1, s'_2)) \in \rightarrow$  iff  $(s_1, a, s'_1) \in \rightarrow_1$  and  $(s_2, a, s'_2) \in \rightarrow_2$ .

It is straightforward to show that  $(T, (\rho_1, id_L), (\rho_2, id_L))$  is a product in the category  $\mathbf{T}_L$ .

**Definition 5** Given  $f_1 = (\sigma_1, id_L) : T_1 \rightarrow U$  and  $f_2 = (\sigma_2, id_L) : T_2 \rightarrow U$



morphisms in  $\mathbf{T}_L$  with  $T_1 = (S_1, i_1, L, \rightarrow_1)$  and  $T_2 = (S_2, i_2, L, \rightarrow_2)$ . We define the pullback of  $f_1$  and  $f_2$  as  $(T, f'_1, f'_2)$  with  $f'_1 : T \rightarrow T_2, f'_2 : T \rightarrow T_1$  as follows:

- $T = (S, i, L, \rightarrow)$  where
  - $S = \{(s_1, s_2) \mid \sigma_1(s_1) = \sigma_2(s_2)\} \subseteq S_1 \times S_2$
  - $i = (i_1, i_2)$
  - $((s_1, s_2), a, (s'_1, s'_2)) \in \rightarrow$  iff  $(s_1, a, s'_1) \in \rightarrow_1$  and  $(s_2, a, s'_2) \in \rightarrow_2$
- $f'_1 = (\rho_2, id_L)$  where  $\rho_2 : S \rightarrow S_2$  is the projection map.
- $f'_2 = (\rho_1, id_L)$  where  $\rho_1 : S \rightarrow S_1$  is the projection map.

We define the path category  $\mathbf{Bran}_L$  as the full subcategory of  $\mathbf{T}_L$  of all synchronization trees with a single finite branch (possibly empty). Now a path in a transition system  $T$  in  $\mathbf{T}_L$  is a morphism  $p : P \rightarrow T$  in  $\mathbf{T}_L$ , with  $P$  an object in  $\mathbf{Bran}_L$ . Clearly this simply means that we look at the traces of the transition system. The  $\mathbf{Bran}_L$ -open maps in  $\mathbf{T}_L$  are characterized as follows:

**Proposition 6** *The  $\mathbf{Bran}_L$ -open morphisms of  $\mathbf{T}_L$  are morphisms  $(\sigma, id_L) : T \rightarrow T'$  with  $T, T' \in \mathbf{T}_L$  such that:*

*If  $\sigma(s) \xrightarrow{a} s'$  in  $T'$ , then there exists  $u \in S$ ,  $s \xrightarrow{a} u$  in  $T$  and  $\sigma(u) = s'$ .*

We now recall the strong notion of bisimulation introduced in [17]. Let  $T_1$  and  $T_2$  be two transition systems in  $\mathbf{T}_L$ , as in Definition 5 above.

**Definition 7** A binary relation  $\mathcal{R} \subseteq S_1 \times S_2$  is a *strong bisimulation* if  $(s, t) \in \mathcal{R}$  implies, for all  $a \in L$ :

- (i) Whenever  $s \xrightarrow{a}_1 s'$  then, there is  $t', t \xrightarrow{a}_2 t'$  and  $(s', t') \in \mathcal{R}$ ,
- (ii) Whenever  $t \xrightarrow{a}_2 t'$  then, there is  $s', s \xrightarrow{a}_1 s'$  and  $(s', t') \in \mathcal{R}$ .

Transition systems  $T_1$  and  $T_2$  are called strongly bisimilar, written  $T_1 \sim T_2$ , if  $(i_1, i_2) \in \mathcal{R}$  for some strong bisimulation relation  $\mathcal{R}$ . The following theorem, proven in [10], shows that the abstract notion of  $\mathbf{Bran}_L$ -bisimilarity coincides with the traditional strong notion of bisimulation.

**Theorem 8 ([10])** *Two transition systems (hence synchronization trees) over the same labeling set  $L$ , are  $\mathbf{Bran}_L$ -bisimilar iff they are strongly bisimilar in the sense of Milner [17].*

In the next sections, we consider the notion of  $\mathbf{P}$ -bisimilarity in the categories of dynamical, control, and hybrid systems.

## 4 Dynamical Systems

The material in this and the subsequent sections require some background knowledge on differential geometry that we have included in the Appendix for the convenience of the reader.

A dynamical system or vector field on a manifold  $M$  is a smooth section of the tangent bundle on  $M$ , that is a smooth map  $X : M \rightarrow TM$  such that  $\pi_M X = id_M$  where  $\pi_M : TM \rightarrow M$  is the canonical projection of the tangent bundle onto the manifold  $M$ .

We proceed to define the model category **Dyn** of dynamical systems. The objects in **Dyn** are dynamical systems  $X : M \rightarrow TM$  where  $M$  is smooth manifold. A morphism in **Dyn** from object  $X : M \rightarrow TM$  to object  $Y : N \rightarrow TN$  is a smooth map  $f : M \rightarrow N$  such that

$$\begin{array}{ccc} M & \xrightarrow{f} & N \\ X \downarrow & & \downarrow Y \\ TM & \xrightarrow{Tf} & TN \end{array}$$

commutes. Thus related systems are said to be *f-related* [12]. The identity morphisms and composition are induced by those in the category **Man** of smooth manifolds and smooth mappings.

We proceed to define the path category **P** as the full subcategory of **Dyn** with objects  $P : I \rightarrow TI$ , where  $P(t) = (t, 1)$  and  $I$  is an open interval of  $\mathbb{R}$  containing the origin. Note that  $I$  is a manifold since it is an open set and it is also parallelizable (trivializable), that is  $TI \cong I \times \mathbb{R}$ . Observe that  $P$  represents the differential equation  $dx(t)/dt = 1$  modeling a clock running on the interval  $I$  at unit rate. Note that any other choice  $P' : I \rightarrow TI$  with  $P'(t) = (t, c)$ ,  $0 \neq c \in \mathbb{R}$ , for path object is isomorphic to  $P : I' \rightarrow TI'$  via  $f(t) = tc$ . Here  $I' = \{t/c \mid t \in I\}$ .

**Definition 9** A *path* or *trajectory* in a dynamical system  $X : M \rightarrow TM$  is a morphism  $c : P \rightarrow X$  in **Dyn**, where  $P$  is an object in **P**. More explicitly, a path  $c$  is a map  $c : I \rightarrow M$  such that the following diagram commutes.

$$\begin{array}{ccc} I & \xrightarrow{c} & M \\ P \downarrow & & \downarrow X \\ TI & \xrightarrow{Tc} & TM \end{array}$$

This means that a path in  $X$  is a smooth map  $c : I \rightarrow M$  for some open

interval  $I$  such that  $c'(t) = X(c(t))$  for all  $t \in I$ . Thus, a path in  $X$  is just an integral curve in  $M$ . Observe that given a path  $c$  in  $X$ , and  $f : X \rightarrow Y$ , then  $f \circ c$  is a path in  $Y$ . This is the sense of  $Y$  *simulating or over-approximating*  $X$ .

The next issue to understand is the meaning of path extension. Suppose  $P : I \rightarrow TI$  and  $Q : J \rightarrow TJ$  are objects in  $\mathbf{P}$  with  $I, J$  open intervals in  $\mathbb{R}$  containing the origin, and  $m : P \rightarrow Q$ . Then,  $m$  is a smooth map from  $I$  to  $J$ , such that  $m'(t) = 1$  or  $m(t) = t - t_0$  for some  $t_0 \in \mathbb{R}$  and for all  $t \in I$ .

We now introduce the following notation: let  $\phi_X(x_1, x_2, t)$  denote the predicate that system  $X$  evolves from state  $x_1$  to state  $x_2$  in time  $|t|$ . Hence,  $\phi_X(x_1, x_2, t)$  is true iff there is an open interval  $I$  in  $\mathbb{R}$  containing the origin and an integral curve  $c : I \rightarrow M$  such that  $c(0) = x_1$  and  $c(t) = x_2$ . The following important result will be central to the characterization of  $\mathbf{P}$ -open maps in  $\mathbf{Dyn}$ .

**Theorem 10** [3] *Let  $X$  be a smooth vector field on a manifold  $M$  and suppose  $p \in M$ . Then there is a uniquely determined open interval of  $\mathbb{R}$ ,  $I(p) = \{\alpha(p) < t < \beta(p)\}$  containing  $t = 0$  and having the properties:*

- (1) *there exists a smooth integral curve  $F(t)$  defined on  $I(p)$  and such that  $F(0) = p$ ;*
- (2) *given any other integral curve  $G(t)$  with  $G(0) = p$ , then the interval of definition of  $G$  is contained in  $I(p)$  and  $F(t) = G(t)$  on this interval.*

The characterization of  $\mathbf{P}$ -open maps is given by the following proposition.

**Proposition 11** *Given the dynamical systems  $X$  on  $M$  and  $Y$  on  $N$ ,  $f : X \rightarrow Y$  is  $\mathbf{P}$ -open if and only if*

*For any state  $x_1 \in M$  of  $X$  and  $t \in \mathbb{R}$ , if  $\phi_Y(f(x_1), y_2, t)$ , then there exists  $x_2 \in M$  such that  $\phi_X(x_1, x_2, t)$  where  $y_2 = f(x_2)$ .*

**PROOF.** Suppose  $f : X \rightarrow Y$  is a  $\mathbf{P}$ -open map and  $\phi_Y(f(x_1), y_2, t)$ . Then there exists a path  $d_1 : J_1 \rightarrow N$  such that  $d_1(0) = f(x_1)$  and  $d_1(t) = y_2$ . Then, by the existence and uniqueness theorem for vector fields there exists a path  $d : J \rightarrow N$  with  $J$  maximal such that  $d(0) = f(x_1)$  and thus  $J_1 \subseteq J$  and  $d_1(t) = d(t)$  for all  $t \in J_1$ . Hence we have a path  $d : J \rightarrow N$  such that  $d(0) = f(x_1)$  and  $d(t) = d_1(t) = y_2$ . On the other hand, there is a path  $c : I \rightarrow M$  with  $c(0) = x_1$  for some open interval  $I$  of  $\mathbb{R}$ . Thus  $fc(0) = f(x_1)$ . By maximality,  $I \subseteq J$  and  $fc(t) = d(t)$  for all  $t \in I$ . Thus the following

diagram (with  $i$  the inclusion map) commutes:

$$\begin{array}{ccc} I & \xrightarrow{c} & M \\ i \downarrow & & \downarrow f \\ J & \xrightarrow{d} & N \end{array}$$

The  $\mathbf{P}$ -openness of  $f$ , then implies that there exists  $r : J \rightarrow M$  such that  $ri = c$  and  $fr = d$ . Hence we have  $ri(0) = c(0) = x_1$  and  $fr(t) = d(t) = y_2$ . Let  $x_2 = r(t)$ , then clearly we have established  $\phi_X(x_1, x_2, t)$ .

Conversely, suppose that the condition of Proposition 11 holds and given  $P, Q, m : P \rightarrow Q$ , with  $p : P \rightarrow X$  and  $q : Q \rightarrow Y$ , the equation  $fp = qm$  holds. Note that as was observed earlier with  $P : I \rightarrow TI$  and  $Q : J \rightarrow TJ$ ,  $m(t) = t - t_0$  for some  $t_0 \in \mathbb{R}$ . Consider the point  $p(0) \in M$ , by Theorem 10 there exists an integral curve  $\tilde{r} : \tilde{I} \rightarrow M$  with  $\tilde{I}$  maximal such that  $\tilde{r}(0) = p(0)$ . We will show that for every  $t \in J, t + t_0 \in \tilde{I}$ . Suppose there exists a  $t \in J$  such that  $t + t_0 \notin \tilde{I}$ . Note that  $q$  is a **Dyn**-morphism, so we have  $\phi_Y(q(-t_0), q(t), t_0 + t)$ , but  $\phi_Y(q(-t_0), q(t), t_0 + t) = \phi_Y(q(m(0)), q(t), t_0 + t) = \phi_Y(f(p(0)), q(t), t_0 + t)$  where the latter equality follows from assumption. Hence, there exists a point  $x \in M$  such that  $\phi_X(p(0), x, t_0 + t)$  such that  $f(x) = q(t)$ . Hence there exists an integral curve  $c : I_c \rightarrow M$  with  $c(0) = p(0)$  and  $c(t + t_0) = x$ , and  $t + t_0 \in I_c \setminus \tilde{I}$  contradicting the maximality of  $\tilde{I}$ . Now define  $r$  by  $r(t) = \tilde{r}(t + t_0)$  for all  $t \in J$ . Clearly  $r$  is a **Dyn**-morphism and is well defined. Now,  $rm(0) = r(-t_0) = \tilde{r}(0) = p(0)$  and hence  $rm = p$ . On the other hand,  $fr(-t_0) = f\tilde{r}(0) = fp(0) = qm(0) = q(-t_0)$  and hence  $fr = q$ .

Intuitively, this condition simply requires that  $p(t), t \in I$  be extendible on both sides if necessary to a solution  $r(t)$  of  $X$  that matches the solution  $q$  of  $Y$ , i.e.  $f(r(t)) = q(t)$  for all  $t \in J$ .

□

In the special case where vector fields are *complete*, that is solutions exist for all time (i.e., for all  $t \in \mathbb{R}$ ), the previous proposition takes the following form.

**Proposition 12** *Let  $X$  and  $Y$  be complete vector fields on manifolds  $M$  and  $N$  respectively . Then any  $f : X \rightarrow Y$  is  $\mathbf{P}$ -open.*

**PROOF.** Note that for complete vector fields any integral curve is defined on the whole of  $\mathbb{R}$ . Suppose  $p : P \rightarrow X$  and  $q : Q \rightarrow Y$  are paths and that  $fp = qm$ . Recall that  $m : P \rightarrow Q$  is given by  $m(t) = t - t_0$  for some  $t_0 \in \mathbb{R}$ . Consider the point  $p(0) \in M$ , then by Theorem 10 and completeness of  $X$ , there exists an integral curve  $d : \mathbb{R} \rightarrow M$  such that  $d(0) = p(0)$ , define

$r : J \rightarrow M$  by  $r(t) = d(t+t_0)$  for all  $t \in J$ . Clearly  $r$  is a **Dyn**-morphism. Now,  $fr(-t_0) = fd(0) = fp(0) = qm(0) = q(-t_0)$  and hence  $fr = q$ . Similarly,  $rm(0) = r(-t_0) = d(0) = p(0)$  and hence  $rm = p$ .

□

Recall that by the general definition in Section 2, two objects  $X_1$  and  $X_2$  in the model category are bisimilar if there is a span of **P**-open maps, that is an object  $X$  with **P**-open maps  $f_1 : X \rightarrow X_1$  and  $f_2 : X \rightarrow X_2$ . The bisimulation relation has to be an equivalence relation and for that purpose one requires the existence of pullbacks in the underlying model category. As is well known in differential geometry [1,12], in **Man** arbitrary pullbacks do not exist. Structure needs to be imposed on the maps in order to guarantee that pullbacks exist.

**Definition 13** Given smooth manifolds  $M$  and  $N$ , a smooth map  $f : M \rightarrow N$  and  $x \in M$ , let  $T_x f : T_x M \rightarrow T_{f(x)} N$  be the derivative of  $f$ . We say that:

- (i)  $f$  is an *immersion* at  $x$  if and only if the map  $T_x f$  is injective.
- (ii)  $f$  is a *submersion* at  $x$  if and only if the map  $T_x f$  is surjective.

**Definition 14** Let  $M, N$  be smooth manifolds and  $f : M \rightarrow N$  be a smooth mapping and  $P$  be a submanifold of  $N$ . The map  $f$  is *transversal* on  $P$  iff for each  $x \in M$  such that  $f(x)$  lies in  $P$ , the composite

$$T_x(M) \xrightarrow{T_x f} T_{f(x)}(N) \rightarrow T_{f(x)}(N)/T_{f(x)}(P)$$

is surjective.

In particular, if for every  $x \in M$ ,  $T_x f$  is surjective, that is, if  $f$  is a submersion on  $M$ , then the composite in the definition above will be surjective and hence every submersion  $f : M \rightarrow N$  is transversal on every submanifold  $P$  of  $N$ . The importance of transversality is that one can prove submanifold property, that is given  $f : M \rightarrow N$  a smooth transversal map on a submanifold  $P$  of  $N$ ,  $f^{-1}(P)$  is a smooth submanifold of  $M$ .

**Definition 15** Given smooth maps  $f : M \rightarrow P$  and  $g : N \rightarrow P$ , we say that  $f$  and  $g$  are transversal if  $f \times g : M \times N \rightarrow P \times P$  is transversal on the diagonal subset  $\Delta_P$  of  $P \times P$ .

**Proposition 16** ([1]) *Let  $M$  and  $N$  be smooth manifolds and  $f : M \rightarrow N$  a smooth map, then  $\text{graph}(f)$  is a smooth submanifold of  $M \times N$ .*

**Proposition 17** *The category **Man** has transversal pullbacks.*

**PROOF.** Suppose  $M, N, P$  are smooth manifolds and  $f_1 : M \rightarrow P$  and  $f_2 : N \rightarrow P$  are smooth transversal maps. Form the fiber product of  $M$  and  $N$  on  $P$ , denoted  $M \times_P N = \{(x, y) \in M \times N \mid f_1(x) = f_2(y)\}$ . As  $f_1$  and  $f_2$  are transversal,  $(f_1 \times f_2)^{-1}\Delta_P$  is a submanifold of  $M \times N$ , the smooth structure is induced by that of  $M \times N$ , for more details see [12]. The rest of the proof consists of checking the universal property of the pullback which follows from the set theoretical construction.

□

Obviously transversality is a sufficient condition and hence there are other pullbacks in the category **Man**. In view of this proposition we have the following result.

**Proposition 18** *Pullbacks of submersions exists in **Man**. Moreover, the pullback of any submersion is a submersion.*

**PROOF.** First note that the transversality condition given in the paper for a given  $f_1 : M \rightarrow P$  and  $f_2 : N \rightarrow P$  is equivalent to the following condition: for any  $p \in P$  such that  $p = f_1(x) = f_2(y)$  for some  $x \in M$  and  $y \in N$ ,  $im(T_x f_1) + im(T_y f_2) = T_p P$  [12]. In other words, the tangent spaces on the left together must span the whole of  $T_p P$ . Now given that  $f_1$  and  $f_2$  are submersions we conclude that  $im(T_x f_1) = im(T_y f_2) = T_p P$  for any  $x \in M$  and  $y \in N$  and hence transversality follows. To prove the second statement, recall that the pullback morphisms are projections restricted to  $M \times_P N$ , let  $g_1 : M \times_P N \rightarrow N$  be the pullback of  $f_1$  (see the diagram below),  $Tg_1 : T(M \times_P N) \cong TM \times_{TP} TN \rightarrow TN$ . Given any  $(x, y) \in M \times_P N$ ,  $T_{(x,y)} g_1 : T_x M \times_{T_{f_1(x)} P} T_y N \rightarrow T_y N$  is surjective as  $f_1$  is a submersion. Hence  $g_1$  is a submersion.

$$\begin{array}{ccc}
 M \times_P N & \xrightarrow{g_1} & N \\
 g_2 \downarrow & & \downarrow f_2 \\
 M & \xrightarrow{f_1} & P
 \end{array}$$

□

After all these preliminary results in the category **Man** of manifolds, we can finally get to our desired goal in the category of dynamical systems.

**Proposition 19** *The category **Dyn** has binary products and transversal pullbacks.*

**PROOF.** Given the dynamical systems  $X : M \rightarrow TM$  and  $Y : N \rightarrow TN$ , define  $X \times Y : M \times N \rightarrow TM \times TN \cong T(M \times N)$  by  $(X \times Y)(x, y) = (X(x), Y(y))$ . The projections  $\pi_1 : X \times Y \rightarrow X$  and  $\pi_2 : X \times Y \rightarrow Y$  are morphisms in **Dyn** as can be easily seen from the definition.

Let  $X, Y$  and  $Z$  be dynamical systems on the manifolds  $M, N, P$  respectively and  $f_1 : X \rightarrow Z$  and  $f_2 : Y \rightarrow Z$ . By assumption the maps  $f_1 : M \rightarrow P$  and  $f_2 : N \rightarrow P$  are transversal, so  $M \times_P N$  is a smooth submanifold of  $M \times N$ . We define the dynamical system  $W : M \times_P N \rightarrow T(M \times_P N) \cong TM \times_{TP} TN$ , denoted  $X \times_P Y$  by  $W = X \times Y|_{M \times_P N}$ . For this definition to be well-defined one has to ensure that for every point  $(x, y) \in M \times_P N$ ,  $(X \times Y)(x, y) \in TM \times_{TP} TN$ , in other words one has to show that the vector field  $X \times Y$  is tangent to the submanifold  $M \times_P N$ . We proceed by proving the equivalent statement: for any  $(x, y) \in M \times_P N$  the flow of  $(x, y)$  along  $X \times Y$  at any time  $t$  (for which the flow is defined), denoted  $Fl_t^{X \times Y}(x, y)$  is in  $M \times_P N$ .

$$(Z \circ f_1)(x) = (Z \circ f_2)(y), \text{ as } (x, y) \in M \times_P N$$

$$T_x f_1 \cdot X(x) = T_y f_2 \cdot Y(y), \text{ as } f_1, f_2 \text{ are } \mathbf{Dyn}\text{-morphisms}$$

$$(\mathcal{L}_X f_1)|_x = (\mathcal{L}_Y f_2)|_y,$$

$$f_1(Fl_t^X(x)) = f_2(Fl_t^Y(y)), \text{ by integration}$$

$$Fl_t^{X \times Y}(x, y) \in M \times_P N, \text{ by definition.}$$

The fact that  $M \times_P N$  is a pullback in the category **Man** implies that  $W$  is a pullback in **Dyn**.

□

In this case, as we have seen above, we can only guarantee the transversal pullbacks. Hence we modify the definition for **P**-bisimulation to ensure that it becomes an equivalence relation. That is we require that there be a span of **P**-open surjective submersions.

**Definition 20** We say that two dynamical systems  $X_1$  and  $X_2$  are **P**-bisimilar, denoted  $X_1 \sim_{\mathbf{P}} X_2$ , if there exists a span of **P**-open surjective submersions  $(Z, f_1 : Z \rightarrow X_1, f_2 : Z \rightarrow X_2)$ .

Note that if there exists a **P**-open surjective submersion  $f : X \rightarrow Y$ , then  $X \sim_{\mathbf{P}} Y$  with the span  $(X, id_X, f)$ .

**Proposition 21** *The relation of **P**-bisimilarity is an equivalence relation on the class of all dynamical systems.*

**PROOF.** Reflexivity follows from the fact that  $id_X$  is a  $\mathbf{P}$ -open surjective submersion for any dynamical system  $X$ . Symmetry is trivial. For transitivity, suppose that  $X_1 \sim_{\mathbf{P}} X_2$  and  $X_2 \sim_{\mathbf{P}} X_3$ . Then there exists the spans  $(Z_1, f_1 : Z_1 \rightarrow X_1, f_2 : Z_1 \rightarrow X_2)$  and  $(Z_2 : g_1 : Z_2 \rightarrow X_2, g_2 : Z_2 \rightarrow X_3)$ . The pullback of  $f_2$  and  $g_1$  exist as these are submersions, denote these pullbacks by  $f'_2$  and  $g'_1$  respectively. We also know that  $f'_2$  and  $g'_1$  are  $\mathbf{P}$ -open surjective submersions as pullback preserves surjectivity. Moreover, composition of  $\mathbf{P}$ -open maps is  $\mathbf{P}$ -open and composition of surjective submersions is a surjective submersion. Thus we have the span of  $\mathbf{P}$ -open surjective submersions  $(Z, f_1 g'_1 : Z \rightarrow X_1, g_2 f'_2 : Z \rightarrow X_3)$  where  $Z$  is the vertex of the pullback square.

□

We proceed with a definition of bisimulation for dynamical systems, for this we need a notion of a well-behaved relation. We will show that bisimulation and  $\mathbf{P}$ -bisimulation coincide. The following definition which seems to be new, is inspired by a relevant definition for equivalence relations on manifolds [1,22].

**Definition 22** Let  $M$  and  $N$  be smooth manifolds and  $\mathcal{R}$  be a relation from  $M$  to  $N$ , that is to say  $\mathcal{R} \subseteq M \times N$ . We say that  $\mathcal{R}$  is *regular* iff

- $\mathcal{R}$  is a smooth submanifold of  $M \times N$ ,
- the projection maps  $\pi_1 : \mathcal{R} \rightarrow M$  and  $\pi_2 : \mathcal{R} \rightarrow N$  are surjective submersions.

**Proposition 23** Let  $X, Y$  and  $Z$  be smooth manifolds and  $\mathcal{R} \subseteq X \times Y$  and  $\mathcal{S} \subseteq Y \times Z$  be regular relations. Then  $\mathcal{S} \circ \mathcal{R} \subseteq X \times Z$  is a regular relation.

**PROOF.** As  $\mathcal{R}$  and  $\mathcal{S}$  are regular relations the following pullback exists

$$\begin{array}{ccc} \mathcal{R} \times_Y \mathcal{S} & \xrightarrow{f_2} & \mathcal{S} \\ f_1 \downarrow & & \downarrow \pi_1 \\ \mathcal{R} & \xrightarrow{\pi_2} & Y \end{array}$$

Note that  $\mathcal{R} \times_Y \mathcal{S} = \{(r, s) \mid \pi_1(s) = \pi_2(r)\} = \{(x, y, y', z) \mid y = y'\}$ . Now consider  $\mathcal{R} \times_Y \mathcal{S} \xrightarrow{\pi_1 \times \pi_2} X \times Z$ , then  $\mathcal{S} \circ \mathcal{R} = (\pi_1 \times \pi_2)(\mathcal{R} \times_Y \mathcal{S})$ . However,  $\pi_1 \times \pi_2$  is a submersion and hence an open map. Thus  $\mathcal{S} \circ \mathcal{R}$  is an open subset of  $X \times Z$  and so a smooth submanifold of  $X \times Z$ . Furthermore,  $\pi_1 : \mathcal{S} \circ \mathcal{R} \rightarrow X$  is given by  $\mathcal{R} \times_Y \mathcal{S} \xrightarrow{f_1} \mathcal{R} \xrightarrow{\pi_1} X$  which is a submersion. Similarly for  $\pi_2 : \mathcal{S} \circ \mathcal{R} \rightarrow Z$ .

□



**Definition 24** Given two dynamical systems  $X$  on  $M$  and  $Y$  on  $N$ , we say that a relation  $\mathcal{R} \subseteq M \times N$  is a *bisimulation* relation iff

- (1)  $\mathcal{R}$  is a regular relation,
- (2) for all  $(x, y) \in M \times N$ ,  $(x, y) \in \mathcal{R}$  implies for all  $t \in \mathbb{R}$ ,
  - if  $\phi_X(x, x', t)$ , there exists  $y' \in N$  such that  $\phi_Y(y, y', t)$  and  $(x', y') \in \mathcal{R}$ ,
  - if  $\phi_Y(y, y', t)$ , there exists  $x' \in M$  such that  $\phi_X(x, x', t)$  and  $(x', y') \in \mathcal{R}$ .

We say that two dynamical systems  $X$  and  $Y$  on manifolds  $M$  and  $N$  respectively are *bisimilar* if there exists a bisimulation relation  $\mathcal{R} \subseteq M \times N$  such that for all  $x \in M$  there exists a  $y \in N$  with  $(x, y) \in \mathcal{R}$  and vice-versa.

**Theorem 25** *Given dynamical systems  $X$  and  $Y$  on manifolds  $M$  and  $N$  respectively,  $X$  and  $Y$  are bisimilar iff they are  $\mathbf{P}$ -bisimilar.*

**PROOF.** Suppose that  $X \sim_{\mathbf{P}} Y$  and  $(Z, f : Z \rightarrow X, g : Z \rightarrow Y)$  is the span where  $Z : P \rightarrow TP$ . Note that  $\text{graph}(f) \subseteq P \times M$  and  $\overline{\text{graph}(g)} \subseteq P \times N$  are regular relations. Consider the converse relation  $\overline{\text{graph}(f)}$  and let  $\mathcal{R} = \text{graph}(g) \circ \overline{\text{graph}(f)}$ . By the proposition above  $\mathcal{R}$  is regular. Let  $(x, y) \in \mathcal{R}$  and  $\phi_X(x, x', t)$ , then there exists a  $z \in P$  such that  $(x, z) \in \overline{\text{graph}(f)}$ , as  $f$  is surjective and  $(z, y) \in \text{graph}(g)$ , so  $x = f(z)$ . As  $f$  is a  $\mathbf{P}$ -open map, then there exist  $z' \in P$  such that  $\phi_Z(z, z', t)$  and  $f(z') = x'$ , i.e.  $(z', x') \in \text{graph}(f)$ . Let  $y' = g(z')$ , then  $\phi_Y(g(z), g(z'), t) = \phi_Y(y, y', t)$  and  $(x', y') \in \mathcal{R}$ . Similarly, the other bisimilarity condition is satisfied.

Conversely, suppose that  $X$  and  $Y$  are bisimilar and  $\mathcal{R}$  is the bisimulation relation. As it is regular, it is a smooth manifold. Consider the dynamical system  $Z : \mathcal{R} \rightarrow T\mathcal{R}$  defined by  $Z = (X \times Y)|_{\mathcal{R}}$ . Note that as in Proposition 19 for  $Z$  to be well defined, one has to show that  $X \times Y$  is tangent to the submanifold  $\mathcal{R}$ . We prove: for any point  $(x, y) \in \mathcal{R}$ ,  $Fl_t^{X \times Y}(x, y) = (Fl_t^X(x), Fl_t^Y(y)) \in \mathcal{R}$ . Let  $Fl_t^X(x) = x'$ , then  $\phi_X(x, x', t)$  and as  $\mathcal{R}$  is a bisimulation relation, there exists  $y'$  such that  $\phi_Y(y, y', t)$  and  $(x', y') \in \mathcal{R}$ , where  $y' = Fl_t^Y(y)$ . Also  $\pi_1 : \mathcal{R} \rightarrow M$  is a surjective submersion. We need to show that  $\pi_1$  is  $\mathbf{P}$ -open. Let  $\phi_X(\pi_1(x, y), x', t) = \phi_X(x, x', t)$ , then there exists  $y'$  such that  $\phi_Y(y, y', t)$  and  $(x', y') \in \mathcal{R}$ , so  $\phi_Z((x, y), (x', y'), t)$  and  $\pi_1(x', y') = x'$ , so  $\pi_1$  is  $\mathbf{P}$ -open. Similarly for  $\pi_2$  and hence  $(Z, \pi_1 : Z \rightarrow X, \pi_2 : Z \rightarrow Y)$  is a span of  $\mathbf{P}$ -open submersions and hence  $X \sim_{\mathbf{P}} Y$ .

□

The above theorem shows that the abstract notion of  $\mathbf{P}$ -bisimilarity coincides with the expected and natural notion of bisimulation for dynamical systems. We now turn our attention to control systems.

The following example contains two bisimilar dynamical systems.

**Example 26** Consider the vector field  $X$  on  $M = \mathbb{R}^2$  defined by  $\dot{x} = Ax$ , where:

$$A = \begin{bmatrix} 1 & 3 \\ 4 & 2 \end{bmatrix}$$

Since  $M$  is a Euclidean space we can make the identification  $TM = \mathbb{R}^2 \times \mathbb{R}^2$  and  $X$  as a map from  $M$  to  $TM$  is described by  $X(x) = (x, Ax)$ . Also consider the vector field  $Y$  on  $N = \mathbb{R}$  defined by  $\dot{y} = 5y$ . The linear map  $f : \mathbb{R}^2 \rightarrow \mathbb{R}$  defined by  $f(x_1, x_2) = x_1 + x_2$  is a **Dyn**-morphism from  $X$  to  $Y$ , indeed:

$$Tf \cdot X(x) = \begin{bmatrix} 1 & 1 \end{bmatrix} \begin{bmatrix} x_1 + 3x_2 \\ 4x_1 + 2x_2 \end{bmatrix} = 5x_1 + 5x_2 = 5(x_1 + x_2) = 5y = Y(f(x))$$

As linear vector fields are known to be complete [3] we have by Proposition 12 that  $f$  is  $P$ -open. Note that  $f$  is a surjective submersion. It then follows that  $X$  and  $Y$  are bisimilar by the span  $(X, id : X \rightarrow X, f : X \rightarrow Y)$ .

## 5 Control Systems

In this section we extend the treatment in the previous section to control systems. The extensions are in many cases straightforward and hence we have omitted the proofs of some propositions and theorems. On the other hand, we give enough details on product and pullback constructions.

We define the model category **Con** as follows. Objects of **Con** are control systems over smooth manifolds, a control system  $X$  over a manifold  $M$  is given by a pair  $(U_M, X_M)$  where  $X_M : M \times U_M \rightarrow TM$  is a smooth map such that  $\pi_M X_M = \pi_1$  with  $\pi_M$  the canonical tangent bundle projection. Here  $U_M$  is a smooth manifold called the *input space*. A morphism in **Con** from a control system  $X = (U_M, X_M)$  to  $Y = (U_N, Y_N)$  is given by a pair  $(\phi_1, \phi_2)$  of smooth maps with  $\phi_1 : M \times U_M \rightarrow N \times U_N$  and  $\phi_2 : M \rightarrow N$ , such that

$$\begin{array}{ccc} M \times U_M & \xrightarrow{\phi_1} & N \times U_N \\ X_M \downarrow & & \downarrow Y_N \\ TM & \xrightarrow{T\phi_2} & TN \end{array} \quad \begin{array}{ccc} M \times U_M & \xrightarrow{\phi_1} & N \times U_N \\ \pi_1 \downarrow & & \downarrow \pi_1 \\ M & \xrightarrow{\phi_2} & N \end{array}$$

both commute. Thus related control systems are said to be  $(\phi_1, \phi_2)$ -related [20]. Note that since  $\pi_1$  is a surjective map,  $\phi_2$  is uniquely determined given  $\phi_1$ . The identity morphism  $id_X : X \rightarrow X$  for an object  $X$  in **Con** is given

by  $id_X = (id_{M \times U_M}, id_M)$ . Given  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$ , the composite  $gf : X \rightarrow Z$  is given by  $gf = (g_1 f_1, g_2 f_2)$ .

The path category  $\mathbf{P}$  is defined as the full subcategory of  $\mathbf{Con}$  with objects control systems  $(U_I, P_I)$  where  $U_I$  is the singleton space with trivial topology and thus  $I \times U_I \cong I$  and  $I$  is an open interval of  $\mathbb{R}$  containing the origin. Hence  $P_I : I \rightarrow TI$  which we define as  $P(t) = (t, 1)$  for all  $t \in I$ . Thus  $(I, P_I)$  is a well defined control system.

**Definition 27** A *path* in a control system  $X = (U_M, X_M)$  is then a morphism  $c = (c_1, c_2) : (U_I, P_I) \rightarrow (U_M, X_M)$  in  $\mathbf{Con}$  with  $c_1 : I \rightarrow M \times U_M$  and  $c_2 : I \rightarrow M$  such that

$$\begin{array}{ccc} I & \xrightarrow{c_1} & M \times U_M \\ P_I \downarrow & & \downarrow X_M \\ TI & \xrightarrow{Tc_2} & TM \end{array} \quad \begin{array}{ccc} I & \xrightarrow{c_1} & M \times U_M \\ id_I \downarrow & & \downarrow \pi_1 \\ I & \xrightarrow{c_2} & M \end{array}$$

commute.

This means that a path in  $X$  is a pair of smooth maps  $c_1 : I \rightarrow M \times U_M$  and  $c_2 : I \rightarrow M$  for some open interval  $I$  with  $0 \in I$  such that  $c'_2(t) = X(c_2(t), u(t))$  for all  $t \in I$ , where  $u(t) = \pi_2 c_1(t)$ . Let  $(I, P_I)$  and  $(J, Q_J)$  be two path objects in  $\mathbf{P}$  and  $m = (m_1, m_2) : P \rightarrow Q$  be a path extension. Then from the diagram on the right above we get that  $m_1 = m_2 : I \rightarrow J$  and then the diagram on the left coincides with the condition we had for dynamical systems. Thus a path extension  $m = (m_1, m_2)$  is of the form  $m_1 = m_2 : I \rightarrow J$ ,  $m_1(t) = t - t_0$  for  $t_0 \in \mathbb{R}$  and for all  $t \in I$ .

**Definition 28** Given control systems  $X = (U_M, X_M), Y = (U_N, Y_N)$  and  $Z = (U_P, Z_P)$ ,  $f = (f_1, f_2) : X \rightarrow Z$  and  $g = (g_1, g_2) : Y \rightarrow Z$  are said to be *transversal* if  $f_2 \times g_2 : M \times N \rightarrow P \times P$  is transversal on  $\Delta_P$  and  $f_1 \times g_1 : (M \times U_M) \times (N \times U_N) \rightarrow (P \times U_P) \times (P \times U_P)$  is transversal on  $\Delta_{P \times U_P}$ .

**Proposition 29** *The category  $\mathbf{Con}$  has binary products and transversal pull-backs.*

**PROOF.** Let  $X = (U_M, X_M)$  and  $Y = (U_N, Y_N)$  be control systems on manifolds  $M$  and  $N$  respectively. Their product  $X \times Y = (U_M \times U_N, (X \times Y)_{M \times N})$  is given by

$$(X \times Y)_{M \times N} := (M \times N) \times (U_M \times U_N) \xrightarrow{\cong} (M \times U_M) \times (N \times U_N) \xrightarrow{X_M \times Y_N} TM \times TN \xrightarrow{\cong} T(M \times N).$$

Suppose now that  $f = (f_1, f_2) : X \rightarrow Z$  and  $g = (g_1, g_2) : Y \rightarrow Z$  where  $Z = (U_P, Z_P)$  is a control system on a smooth manifold  $P$ . The pullback of  $f$  and  $g$  is given by  $(Q, f', g')$  where  $Q$  is a control system on the manifold  $M \times_P N$  with input space  $U_M \times_P U_N := (\pi_2 \times \pi_2)((f_1 \times g_1)^{-1} \Delta_{P \times U_P})$  which is a submanifold of  $U_M \times U_N$  due to transversality of  $f_1$  and  $g_1$  and the fact that  $\pi_2 \times \pi_2$  is an open map. The dynamics  $X_M \times_P Y_N$  is defined by restricting  $X_M \times Y_N$  to  $(M \times_P N) \times (U_M \times_P U_N)$ , see the proof of Proposition 19.

□

We introduce the following notation: let  $\phi_X(x_1, x_2, t)$  denote the predicate that system  $X = (U_M, X_M)$  evolves from state  $x_1$  to state  $x_2$  in time  $t$ , under some input in  $U_M$ . Hence,  $\phi_X(x_1, x_2, t)$  is true iff there is an open interval  $I$  of  $\mathbb{R}$  containing the origin, a morphism  $c = (c_1, c_2) : (U_I, P_I) \rightarrow X$  such that  $c_2(0) = x_1$  and  $c_2(t) = x_2$ . The input deriving the system is given by  $\pi_2 c_1 : I \rightarrow U_M$ . Similarly to the case of dynamical systems, we characterize the **P**-open maps as follows.

**Proposition 30** *Given the control systems  $X = (U_M, X_M)$  and  $Y = (U_N, Y_N)$ ,  $f = (f_1, f_2) : X \rightarrow Y$  is **P**-open iff*

*For any state  $x_1 \in M$  of  $X$  and  $t \in \mathbb{R}$ , if  $\phi_Y(f_2(x_1), y_2, t)$ , then there exists  $x_2 \in M$  such that  $\phi_X(x_1, x_2, t)$  where  $y_2 = f_2(x_2)$ .*

**Definition 31** Given control systems  $X = (U_M, X_M)$  and  $Y = (U_N, Y_N)$ , a morphism  $f : X \rightarrow Y$  is said to be a *surjective submersion* if both its components  $f_1$  and  $f_2$  are surjective submersions.

**Definition 32** We say that two control systems  $X_1$  and  $X_2$  are **P**-bisimilar, denoted  $X_1 \sim_{\mathbf{P}} X_2$  if there exists a span of **P**-open surjective submersions  $(Z, f_1 : Z \rightarrow X_1, f_2 : Z \rightarrow X_2)$ .

**Proposition 33** *The relation of **P**-bisimilarity is an equivalence relation on the class of all control systems.*

We define the bisimulation relation for control systems, similarly to the case of dynamical systems.

**Definition 34** Given two control systems  $X = (U_M, X_M)$  and  $Y = (U_N, Y_N)$ , we say that a relation  $\mathcal{R} \subseteq M \times N$  is a *bisimulation* relation iff

- (1)  $\mathcal{R}$  is a regular relation,
- (2) for all  $(x, y) \in M \times N$   $(x, y) \in \mathcal{R}$  implies, for all  $t \in \mathbb{R}$ ,
  - if  $\phi_X(x, x', t)$ , there exists  $y' \in N$  such that  $\phi_Y(y, y', t)$  and  $(x', y') \in \mathcal{R}$ ,
  - if  $\phi_Y(y, y', t)$ , there exists  $x' \in M$  such that  $\phi_X(x, x', t)$  and  $(x', y') \in \mathcal{R}$ .

We say that two control systems  $X$  and  $Y$  as above are *bisimilar* if there exists a bisimulation relation  $\mathcal{R} \subseteq M \times N$  such that for all  $x \in M$  there exists a  $y \in N$  with  $(x, y) \in \mathcal{R}$  and vice-versa.

**Theorem 35** *Given control systems  $X = (U_M, X_M)$  and  $Y = (U_N, Y_N)$ ,  $X$  and  $Y$  are bisimilar if and only if they are  $\mathbf{P}$ -bisimilar.*

The above theorem, shows that the categorical notion of bisimulation described in Section 2, also captures the natural notion of bisimulation for control systems.

## 6 Hybrid Systems

A hybrid system is just a family of smooth dynamical systems parameterized over the states of an underlying labelled transition system. The dynamical systems are glued together by the transitions of the underlying labelled transition system.

**Definition 36** *A hybrid (dynamical) system  $H$  is a tuple*

$$H = (S, i, L, \rightarrow, \{X_s\}_{s \in S}, \{Inv_s\}_{s \in S}, \{G_{s,a}\}_{s=src(a), a \in L}, \{R_{s,a}\}_{s=src(a), a \in L})$$

where:

- $(S, i, L, \rightarrow)$  is a labelled transition system,
- $X_s$  is a smooth dynamical system  $X_s : M_s \rightarrow TM_s$ , for each  $s \in S$ , notice that we do not require that the dynamical systems be identical, nor do we require that the underlying manifolds be the same for all states  $s \in S$ ,
- $Inv_s \subseteq M_s$ , for each  $s \in S$  is called *the invariant set* at state  $s$ ,  $Inv_s$  is not required to be a submanifold,
- $G_{s,a} \subseteq Inv_s$  called the *guard* of the transition  $a \in L$ , for each  $a \in L$ , where  $s$  is the source of the action  $a$ , that is there is  $t \in S$  such that  $(s, a, t) \in \rightarrow$ .
- With  $(s, a, t) \in \rightarrow$ ,  $R_{s,a} : G_{s,a} \rightarrow Inv_t$  is a function, called the *reset* function.

Note that we have indexed the guard and the reset functions on a subset of  $S \times L$  due to the fact that there might be two different edges with the same label  $a$  and different source states and these might very well have different guards, identically labelled edges emerging from the same state will have identical guards and reset functions.

**Example 37** *We give an example of a hybrid system below, see Figure 1. In this example  $M_{s_i} = \mathbb{R}$  for  $i = 1, 2, 3$  and guards are given by:  $G_{s_1,a} = [1/2, 1[$ ,  $G_{s_2,b} = ] - 1, 1[$  and  $G_{s_3,c} = \{1/4\}$ .*

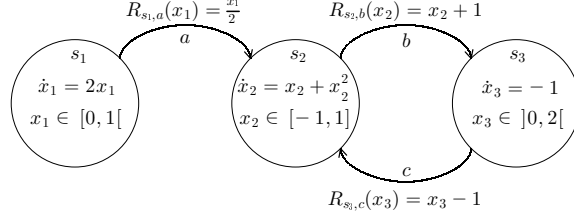


Fig. 1. Hybrid System  $H$

In order to simplify the notation we refer to the underlying transition system in a hybrid system  $H$ , by  $T$ , that is for a hybrid system as above  $T = (S, i, L, \rightarrow)$ . We will also omit the index sets, as it will always be clear from the context. We assume that the underlying transition systems all have the same label set  $L$ , that is  $T$  is an object in  $\mathbf{T}_L$ .

Given a hybrid system  $H = (T, X_s, Inv_s, G_{s,a}, R_{s,a})$ , the state space of  $H$  is defined by  $Q = \{(s, x) \mid s \in S \text{ and } x \in Inv_s\} = \biguplus_{s \in S} Inv_s$ . We next define a transition relation on a hybrid system as follows  $\Rightarrow \subseteq Q \times (L \cup \{\tau_t\}_{t \in \mathbb{R}_0^+}) \times Q$ . For  $t \in \mathbb{R}_0^+$ ,  $\tau_t \notin L$  are distinguished actions used to represent the continuous flow of the system. We let  $(s, x) \xrightarrow{a} (s', x')$  denote  $((s, x), a, (s', x')) \in \Rightarrow$ . Given states  $(s, x), (s', x')$  in  $Q$ ,  $(s, x) \xrightarrow{a} (s', x')$  iff either one of the following transitions takes place:

- (1) *discrete transition* ( $a \in L$ ):  $s \xrightarrow{a} s'$ , i.e.,  $a$  is a transition in  $T$ , and  $x \in G_{s,a}$  and  $x' = R_{s,a}(x)$ . Note that  $x \in M_s$  and  $x' \in M_{s'}$  and  $M_s$  may be different from  $M_{s'}$ .
- (2) *continuous transition* ( $a = \tau_t, t \in \mathbb{R}_0^+$ ):  $s = s'$  and  $Fl_t^{X_s}(x) = x'$  and  $Fl_{t'}^{X_s}(x) \in Inv_s$  for all  $t' \in [\alpha, \alpha + t]$  where  $\alpha$  is the time when the flow begins.

In other words, the flow in the dynamical system  $X_s$  takes  $x$  to  $x'$  while satisfying the invariant at all times in between, while the discrete state remains the same.

**Example 38** *Here is an example of a trajectory that can take place in the hybrid system  $H$  of Example 37.*

*System starts at  $(s_1, x_1(0) = 1/4)$  and flows continuously for  $\log 2/2$  units of time reaching  $(s_1, x_1(\log 2/2) = 1/2)$ . At this point the guard is enabled and discrete transition  $a$  occurs making the system evolve from  $(s_1, 1/2)$  to  $(s_2, R_{s_1,a}(1/2)) = (s_2, 1/4)$ . Now discrete transition  $b$  takes place and the system jumps to  $(s_3, 1/4 + 1) = (s_3, 5/4)$ . At this point the system flows continuously for 1 unit of time until reaching  $(s_3, x_3(\log 2/2 + 1) = 1/4)$  and  $c$  takes the system to  $(s_2, -3/4)$ .*

This can be neatly represented as

$$(s_1, 1/4) \xrightarrow{\tau_{\log 2/2}} (s_1, 1/2) \xrightarrow{a} (s_2, 1/4) \xrightarrow{b} (s_3, 5/4) \xrightarrow{\tau_1} (s_3, 1/4) \xrightarrow{c} (s_2, -3/4)$$

We define the model category **Hyb** with objects, hybrid systems. A morphism  $f$  in **Hyb** from  $H = (T, X, Inv, G, R)$  to  $H' = (T', X', Inv', G', R')$  with  $T = (S, i, L, \rightarrow)$  and  $T' = (S', i', L, \rightarrow')$  is a pair  $(f^1, \{f_s^2\}_{s \in S})$  where

- $f^1 : T \rightarrow T'$  is a  $\mathbf{T}_L$ -morphism,
- $f_s^2 : X_s \rightarrow X'_{f^1(s)}$  is a **Dyn**-morphism for all  $s \in S$ ,
- $f_s^2(Inv_s) \subseteq Inv'_{f^1(s)}$  for all  $s \in S$ , and
- $f_s^2(G_{s,a}) \subseteq G'_{f^1(s),a}$  for all  $s \in S$ ,
- $((s, x), a, (s', x')) \in \Rightarrow, (x, x') \in R_{s,a}$  implies  $(f_s^2(x), f_{s'}^2(x')) \in R'_{f^1(s),a}$ .

For hybrid systems  $H = (T, X, Inv, G, R)$ ,  $H' = (T', X', Inv', G', R')$  and  $H'' = (T'', X'', Inv'', G'', R'')$ , the identity morphism  $id : H \rightarrow H$  is defined by  $id_H = (id_T, \{id_{X_s}\}_s)$ . Given  $f : H \rightarrow H'$  and  $g : H' \rightarrow H''$ , their composition  $h = gf$  is given by  $h^1 = g^1 f^1$  and  $h_s^2 = g_{f^1(s)}^2 f_s^2$  for  $s \in S$ . It can be easily observed that hybrid systems and their morphisms form a category.

**Example 39** Consider the hybrid systems  $\tilde{H}$ ,  $H'$  and  $H''$  in Figures 2, 3 and 4 respectively.

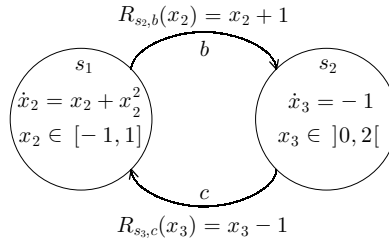


Fig. 2. Hybrid System  $\tilde{H}$ .

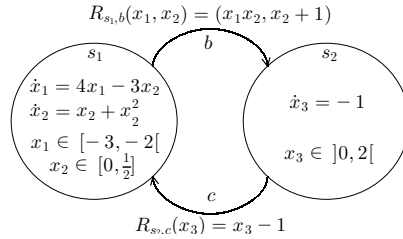


Fig. 3. Hybrid System  $H'$ .

Note that on the figures we have avoided adding tilde, prime and double prime to the symbols to avoid notational complexity, instead we make such references to variables in the text. The guards in  $\tilde{H}$ ,  $H'$  and  $H''$  will play no role in this example, hence we leave them unspecified.

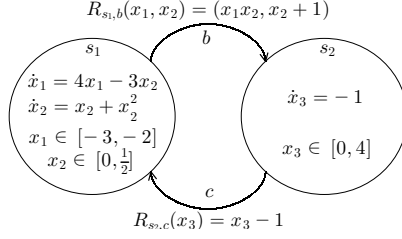


Fig. 4. Hybrid System  $H''$ .

We first show that there is a morphism from  $H'$  to  $\tilde{H}$ . Let  $f^1$  be defined by  $f^1(s'_1) = \tilde{s}_1$  and  $f^1(s'_2) = \tilde{s}_2$ ,  $f_{s'_1}^2$  be defined by  $f_{s'_1}^2(x_1, x_2) = x_2$  and finally  $f_{s'_2}^2$  be the identity map, it is obvious that the conditions for  $f_{s'_2}^2$  are satisfied. For  $f_{s'_1}^2$  we note that:

$$Tf_{s'_1}^2 \cdot \begin{bmatrix} 4x_1 - 3x_2 \\ x_2 + x_2^2 \end{bmatrix} = x_2 + x_2^2$$

which shows that  $f_{s'_1}^2$  is a **Dyn**-morphism. The remaining conditions are easily checked.

Next we show that there are no morphisms from  $H''$  to  $\tilde{H}$ . This follows from the fact that  $Tf_{s'_2}^2 \cdot (-1) = -1$  implies that  $f_{s'_2}^2(y) = y + c$  for some constant  $c$ . However, then for all  $c$ ,  $f_{s'_2}^2(Inv_{s''_2}) \not\subseteq Inv_{\tilde{s}_2}$ .

We proceed to define the path category  $\mathbf{P}$  as the full subcategory of **Hyb** with objects  $P = (T, X, Inv, G, R)$  where  $T = (S, i, L, \rightarrow)$  is a tree with a single (possibly empty) branch, and for every  $s \in S$ ,  $X_s : I_s \rightarrow TI_s$ , with  $I_s$  an open interval  $(\alpha_s, \beta_s)$  of  $\mathbb{R}$  containing the origin and  $X_s(t) = (t, 1)$ .  $Inv_s \subseteq I_s$ ,  $Inv_s$  is a closed interval of the form  $[t_1, t_2]$  for some  $t_1, t_2$ , (this includes  $t_1 = t_2$  possibility) that represents the duration of the continuous flow and  $G_{s,a} = \{t_2\}$ . Suppose  $(s, a, t) \in \rightarrow$ ,  $R_{s,a} : G_{s,a} \rightarrow Inv_t$  is the inclusion function. Clearly this requires that  $G_{s,a} \subseteq Inv_t$ .

**Definition 40** A path or trajectory in a hybrid system  $H$  is a morphism  $p : P \rightarrow H$  in **Hyb**, where  $P$  is an object in  $\mathbf{P}$ .

Any path including a discrete transition will also carry the information of when this transition takes place. This in turn is captured by the choice of the appropriate path object (see the example below). The example below contains the representative cases that cover all possibilities. We content ourselves with the example as it is sufficiently self explanatory.

**Example 41** Let  $H$  be a hybrid system. We will consider 3 path examples that cover all possible cases.



- Consider a path of the form

$$(s_0, x_0) \xrightarrow{\tau_t} (s_0, x'_0) \xrightarrow{a} (s_1, x_1) \xrightarrow{\tau_{t_1}} (s_1, x'_1) \xrightarrow{b} (s_2, x_2)$$

so in this case the system flows for duration  $t$ , starting at time 0 and then at time  $t$  the event  $a$  takes place etc. This path is represented by the path object  $P$  which has states  $l_0, l_1, l_2$  as shown below:

$$l_0 \xrightarrow{a} l_1 \xrightarrow{b} l_2$$

$$\begin{array}{lll} I_{l_0} = (\alpha_0, \beta_0) & I_{l_1} = (\alpha_1, \beta_1) & I_{l_2} = (\alpha_2, \beta_2) \\ \text{with } 0, t \in I_{l_0} & \text{with } 0, t + t_1 \in I_{l_1} & \text{with } 0, t + t_1 \in I_{l_2} \\ \text{Inv}_{l_0} = [0, t] & \text{Inv}_{l_1} = [t, t + t_1] & \text{Inv}_{l_2} = \{t + t_1\} \\ G_{l_0, a} = \{t\} & G_{l_1, b} = \{t + t_1\} & \\ R_{l_0, a}(t) = t & R_{l_1, b}(t + t_1) = t + t_1 & \end{array}$$

In this case we also spell out the definition of  $p : P \rightarrow H : p^1(l_j) = s_j, j = 0, 1, 2$  and  $p_{l_0}^2(0) = x_0, p_{l_1}^2(t) = x_1$  and  $p_{l_2}^2(t + t_1) = x_2$ , note that the  $p_s^2$  are integral curves and thus uniquely determined by these definitions.

- Next consider the path

$$(s_0, x_0) \xrightarrow{\tau_t} (s_0, x'_0) \xrightarrow{a} (s_1, x_1) \xrightarrow{b} (s_2, x_2) \xrightarrow{\tau_{t_1}} (s_2, x'_2)$$

The path object for this path is defined as follows, the underlying tree is the same as the one above and we have:

$$\begin{array}{lll} I_{l_0} = (\alpha_0, \beta_0) & I_{l_1} = (\alpha_1, \beta_1) & I_{l_2} = (\alpha_2, \beta_2) \\ \text{with } 0, t \in I_{l_0} & \text{with } 0, t \in I_{l_1} & \text{with } 0, t + t_1 \in I_{l_2} \\ \text{Inv}_{l_0} = [0, t] & \text{Inv}_{l_1} = \{t\} & \text{Inv}_{l_2} = [t, t + t_1] \\ G_{l_0, a} = \{t\} & G_{l_1, b} = \{t\} & \\ R_{l_0, a}(t) = t & R_{l_1, b}(t) = t & \end{array}$$

- This last case follows from the one above, but we include it for the sake of clarity. Suppose we are given the path

$$(s_0, x_0) \xrightarrow{a} (s_1, x_1) \xrightarrow{\tau_t} (s_1, x'_1) \xrightarrow{b} (s_2, x_2)$$

The path object here too has the same underlying tree as the ones above and

$$\begin{array}{lll} I_{l_0} = (\alpha_0, \beta_0) & I_{l_1} = (\alpha_1, \beta_1) & I_{l_2} = (\alpha_2, \beta_2) \\ \text{with } 0 \in I_{l_0} & \text{with } 0, t \in I_{l_1} & \text{with } 0, t \in I_{l_2} \\ \text{Inv}_{l_0} = \{0\} & \text{Inv}_{l_1} = [0, t] & \text{Inv}_{l_2} = \{t\} \\ G_{l_0, a} = \{0\} & G_{l_1, b} = \{t\} & \\ R_{l_0, a}(0) = 0 & R_{l_1, b}(t) = t & \end{array}$$

Suppose  $P = (T, X, \text{Inv}, G, R)$  and  $P' = (T', X', \text{Inv}', G', R')$  and  $m : P \rightarrow P'$ . Then,  $m^1 : T \rightarrow T'$  which simply extends the tree  $T$  to  $T'$ . For any  $s \in S$ ,  $m_s^2$

is a smooth map from  $I_s$  to  $I_{m^1(s)}$ , such that  $d/dt(m_s^2(t)) = 1$  or  $m_s^2(t) = t - t_0$  for some  $t_0 \in \mathbb{R}$  and for all  $t \in I_s$ .

We next characterize the **P**-open maps.

**Proposition 42** *Let  $H = (T, X_s, Inv_s, G_{s,a}, R_{s,a})$  and  $H' = (T', X'_s, Inv'_s, G'_{s,a}, R'_{s,a})$  be hybrid systems with  $T = (S, i, L, \rightarrow)$ ,  $T' = (S', i', L, \rightarrow')$  and underlying state spaces  $Q$  and  $Q'$ , then  $f = (f^1, f^2) : H \rightarrow H'$  is **P**-open iff*

- (i) *for all  $u \in Q, w \in Q'$  and  $a \in L$ , if  $f(u) \xrightarrow{a} w$ , then there exists a  $v \in Q$  such that  $u \xrightarrow{a} v$  and  $f(v) = w$ , and*
- (ii) *for all  $u \in Q, w \in Q'$  and  $t \in \mathbb{R}_0^+$ , if  $f(u) \xrightarrow{t} w$ , then there exists a  $v \in Q$  such that  $u \xrightarrow{t} v$  and  $f(v) = w$ .*

**PROOF.** Suppose  $f = (f^1, f^2) : H \rightarrow H'$  is **P**-open and for a reachable state  $u = (s, x) \in Q$ ,  $f(u) \xrightarrow{a} w$  in  $H'$ . Let  $w = (s'', x'')$ , then  $f(u) = (f^1(s), f^2(x))$  and  $f^1(s) \xrightarrow{a} s''$  in  $T'$ ,  $f^2(x) \in G_{f^1(s), a}$  and  $(f^2(x), x'') \in R_{f^1(s), a}$ . As  $u = (s, x)$  is reachable in  $H$ , the state  $s \in S$  is reachable from  $i$  in  $T$ , say through

$$i = s_0 \xrightarrow{a_1} s_1 \dots \xrightarrow{a_n} s_n = s$$

hence there is a path object  $P$  whose underlying tree is

$$l_0 \xrightarrow{a_1} l_1 \dots \xrightarrow{a_n} l_n$$

and a path  $p : P \rightarrow H$  with  $p^1(l_0) = s_0, \dots, p^1(l_n) = s_n$  and appropriate  $p_s^2$  for  $s \in \{l_0, \dots, l_n\}$ . The only part of the continuous data about  $P$  relevant to the proof is the information at  $l_n$  which we will make explicit below. Suppose that  $a_n$  occurs at time  $t_n$  and consider the following cases:

**Case 1:** No continuous flow takes place at state  $s_n$ , hence we have, say  $(s_{n-1}, x) \xrightarrow{a_n} (s_n, x)$ , or  $(s_{n-1}, x') \xrightarrow{a_n} (s_n, x)$  with  $R_{s_{n-1}, a_n}(x') = x$ . Also  $I_{l_n} = (\alpha_n, \beta_n)$  containing the origin and  $t_n$  and  $Inv_{l_n} = \{t_n\}$ . Define a path object  $P'$  with underlying tree

$$l'_0 \xrightarrow{a_1} l'_1 \dots \xrightarrow{a_n} l'_n \xrightarrow{a} l'$$

The underlying continuous information is the same as in  $P$  except that we set  $G_{l'_n, a} = \{t_n\}$ , and  $I_{l'} = (\alpha', \beta')$  containing the origin and  $t_n$  and  $Inv_{l'} = \{t_n\}$ . Also we define the path  $q : P' \rightarrow H'$  by  $q^1(l'_j) = f^1 p^1(l_j)$  for  $j = 0, \dots, n$ , and  $q^1(l') = s''$ . And  $q_s^2 = f_s^2 p_s^2$  for all  $s \in \{l'_0, \dots, l'_n\}$ , and  $q_{l'}^2(t_n) = x''$ .

**Case 2:** There is a continuous flow at  $s_n$ , say we have

$$(s_{n-1}, x') \xrightarrow{a_n} (s_n, \tilde{x}) \xrightarrow{\tau_i} (s_n, x)$$

for some  $t$ . The path object  $P$  is as above save for  $I_{l_n} = (\alpha_n, \beta_n)$  containing the origin, and  $t_n + t$  and  $Inv_{l_n} = [t_n, t_n + t]$ . We define the path object  $P'$  as this new path object  $P$ , except for  $G_{l'_n, a} = \{t_n + t\}$ , and  $I_{l'} = (\alpha', \beta')$  containing the origin and  $t_n + t$  and  $Inv_{l'} = \{t_n + t\}$ . The morphism  $q$  is defined as above except that we set  $q_{l'}^2(t_n + t) = x''$ .

Clearly  $q$  is a path and with  $m$  the obvious embedding we have  $fp = qm$ . As  $f$  is  $\mathbf{P}$ -open we have  $r : P' \rightarrow H$ , let  $v = (r^1(l'), r_{l'}^2(t_n))$  in case 1 and  $v = (r^1(l'), r_{l'}^2(t_n + t))$  in the second case. Clearly  $u \xrightarrow{a} v$  and

$$f(v) = (f^1 r^1(l'), f_{r^1(l')}^2(r_{l'}^2(t_n))) = (s'', x'')$$

in case 1 and similarly  $f(v) = w$  in case 2.

Now suppose  $f(u) \xrightarrow{\tau'_i} w$ , with the same notation as above, this means that  $f^1(s) = s''$  and  $Fl_{l'}^{X' f^1(s)}(f_s^2(x)) = x''$ . Again we need to distinguish two cases similar to those above: (1) There is no continuous flow at  $s_n$ . The path object  $P$  is the same as in case 1 above, we define the path object  $P'$ :

$$l'_0 \xrightarrow{a_1} l'_1 \quad \dots \quad \xrightarrow{a_n} l'_n$$

as  $P$  except that we set  $I_{l'_n} = (\alpha', \beta')$  containing 0 and  $t_n + t'$ ,  $Inv_{l'_n} = [t_n, t_n + t']$ . The path  $q$  is defined as in case 1 above except that  $q_{l'_n}^2(t_n + t') = x''$ .

(2) There is continuous flow, say of duration  $t$  to reach  $(s, x)$ , in this case  $P$  is the same as in case 2 above and we define  $P'$  as  $P$  except that  $I_{l'_n} = (\alpha', \beta')$  to contain the origin and  $t_n + t + t'$  and  $Inv_{l'_n} = [t_n, t_n + t + t']$ .

It can be easily checked that with  $v = (r^1(l'_n), r_{l'_n}^2(t_n + t'))$ , and  $v = (r^1(l'_n), r_{l'_n}^2(t_n + t + t'))$  in cases 1 and 2 respectively, one has  $u \xrightarrow{\tau'_i} v$  and  $f(v) = w$ .

Conversely, suppose that conditions (i) and (ii) of the proposition hold and that there are paths  $p : P \rightarrow H$  and  $q : P' \rightarrow H'$  with  $m : P \rightarrow P'$  such that  $fp = qm$  we need to show that  $f$  is  $\mathbf{P}$ -open.

Note that the underlying tree of  $P'$  is either the same as or an extension of  $P$ , in this case we repeatedly use condition (i) above to define  $r^1$ . The argument for the definition of  $r^1$  is the same as in [10]. we show the proof on an example,

suppose  $P$  is given by

$$l_0 \xrightarrow{a} l_1$$

which maps to

$$s_0 \xrightarrow{a} s_1$$

in  $H$  under  $p$  and  $P'$  is given by

$$l'_0 \xrightarrow{a} l'_1 \xrightarrow{b} l'_2$$

which maps to

$$s'_0 \xrightarrow{a} s'_1 \xrightarrow{b} s'_2$$

under  $q$ .

Now apply condition (i) of the proposition to find  $s_2$  such that  $s_1 \xrightarrow{b} s_2$  and define  $r^1(l'_j) = s_j$ ,  $j = 0, 1, 2$ .

Consider the commutative diagram

$$\begin{array}{ccc} I_{l_0} & \xrightarrow{p_{l_0}^2} & M_{s_0} \\ m_{l_0}^2 \downarrow & & \downarrow f_{s_0}^2 \\ I_{l'_0} & \xrightarrow{q_{l'_0}^2} & M_{s'_0} \end{array}$$

and use Theorem 11 to define  $r_{l'_0}^2$ , similarly for  $r_{l'_1}^2$ . As for  $r_{l'_2}^2$ , suppose  $Inv_{l'_2} = \{t_b\}$  where  $t_b$  is the time that  $b$  occurs. Then there is no continuous flow at  $s'_2$  and we set  $r_{l'_2}^2(t_b) = x_2$  where  $(s_1, x_1) \xrightarrow{b} (s_2, x_2)$ . On the other hand, if time  $t$  elapsed at state  $l'_2$ , use (ii) above to find  $(s_2, x'_2)$  where  $(s_2, x_2) \xrightarrow{\tau} (s_2, x'_2)$  and set  $r_{l'_2}^2(t_b) = x_2$  and  $r_{l'_2}^2(t_b + t) = x'_2$ .

It is not hard to see that with this definition  $r : P' \rightarrow H$  is a path and that the  $fr = p'$  and  $rm = p$ .

□

**Definition 43** Let  $H', H''$  be hybrid systems with  $S'$  and  $S''$  as the state spaces of their underlying labelled transition systems respectively. Let  $f : H' \rightarrow \tilde{H}$  and  $g : H'' \rightarrow \tilde{H}$  be morphisms of hybrid systems. We say that  $f$  and  $g$  are *transversal* if for any  $s' \in S'$  and  $s'' \in S''$  such that  $f^1(s') = g^1(s'')$

we have that the **Dyn**-morphisms  $f_{s'}^2 : X'_{s'} \rightarrow \tilde{X}_{f^1(s')}$  and  $g_{s''}^2 : X''_{s''} \rightarrow \tilde{X}_{g^1(s'')}$  are transversal (see Section 4).

**Proposition 44** *The category **Hyb** has binary products and transversal pullbacks.*

**PROOF.** Given two hybrid systems

$$H' = (T', X', Inv', G', R')$$

and

$$H'' = (T'', X'', Inv'', G'', R'')$$

with  $T' = (S', i', L, \rightarrow')$  and  $T'' = (S'', i'', L, \rightarrow'')$ , we define their product  $H = H' \times H'' = (T, X, Inv, G, R)$  as follows:

- $T = (S, i, L, \rightarrow) = T' \times T''$ . Note that this is the product in the category  $\mathbf{T}_L$  of transition systems with label set  $L$  (see Section 3 above.)
- For  $s = (s', s'') \in S = S' \times S''$ ,  $X_s = X'_{s'} \times X''_{s''}$ , which is a product in **Dyn**.
- For  $s = (s', s'') \in S$ ,  $Inv_s = Inv'_{s'} \times Inv''_{s''}$ , Cartesian product of sets.
- Finally, for  $s = (s', s'') \in S$ ,  $G_{(s', s''), a} = G'_{s', a} \times G''_{s'', a}$  and  $R_{(s', s''), a} = R'_{s', a} \times R''_{s'', a}$

Definition of projection maps is based on those for underlying transition and dynamical systems and verification of product property is routine and not included.

Let  $H', H''$  be hybrid systems as above and  $f : H' \rightarrow \tilde{H}$  and  $g : H'' \rightarrow \tilde{H}$  be morphisms of hybrid systems. Now suppose  $f, g$  are transversal, we define the pullback of  $f$  and  $g$  as  $(H, g', f')$  where  $H = (T, X, Inv, G, R)$  is given by

- $T$  is the pullback in  $\mathbf{T}_L$  of  $f^1, g^1$ , (see Section 3 above.) Recall that then  $S = \{(s', s'') \mid f^1(s') = g^1(s'')\}$ .
- For  $s = (s', s'') \in S$ ,  $X_s$  is the pullback in **Dyn** of transversal maps  $f_{s'}^2$  and  $g_{s''}^2$  (see Section 4 above). Recall that  $M_s = \{(x', x'') \in M'_{s'} \times M''_{s''} \mid f_{s'}^2(x') = g_{s''}^2(x'')\}$
- For  $s = (s', s'')$ ,  $Inv_s = \{(x', x'') \in Inv'_{s'} \times Inv''_{s''} \mid f_{s'}^2(x') = g_{s''}^2(x'')\}$
- Finally  $G_{(s', s''), a} = \{(x', x'') \in G'_{s', a} \times G''_{s'', a} \mid f_{s'}^2(x') = g_{s''}^2(x'')\}$  and

$$R_{(s', s''), a} = \{(x', x'') \in R'_{s', a} \times R''_{s'', a} \mid f_{s'}^2(x') = g_{s''}^2(x'')\}.$$

Definition of  $f'$  and  $g'$  follow using the underlying morphisms and verification of pullback property is routine and not included.

□

**Definition 45** We say that two hybrid systems  $H$  and  $H'$  are **P**-bisimilar if there exists a span of **P**-open surjective submersions  $(\tilde{H}, f : \tilde{H} \rightarrow H, g : \tilde{H} \rightarrow H')$ . That is, for any  $\tilde{s} \in \tilde{S}$ ,  $f_{\tilde{s}}^2$  and  $g_{\tilde{s}}^2$  are surjective submersions.

This immediately gives us the following result.

**Proposition 46** **P**-bisimilarity is an equivalence relation on the class of all hybrid systems

It remains to show that the notion of **P**-bisimilarity coincides with a natural notion of bisimulation for hybrid systems, that we now define.

**Definition 47** Given two hybrid systems  $H = (T, X, Inv, G, R)$  and  $H' = (T', X', Inv', G', R')$ , with  $X_s$  and  $X'_{s'}$  defined on  $M_s$  and  $M'_{s'}$  respectively. Let  $R^1 \subseteq S \times S'$ , and for  $(s, s') \in R^1$ , let  $R^2_{s,s'} \subseteq M_s \times M'_{s'}$  be a family of regular relations.

Define  $\mathcal{R} = (R^1, \{R^2_{s,s'}\}_{(s,s') \in R^1})$  to be the set

$$\{(s, x, s', x') \mid (s, s') \in R^1 \text{ and } (x, x') \in R^2_{s,s'}\}.$$

Notice that  $\mathcal{R}$  is not a relation from  $Q$  to  $Q'$ , as it might contain tuples  $(s, x, s', x')$  with  $x \notin Inv_s$  or  $x' \notin Inv'_{s'}$ . However, in our definition below this fact poses no problems, as the hybrid system always evolves inside the invariant sets. Such a relation is said to be a *bisimulation* relation iff for all  $((s, x), (s', x')) \in Q \times Q'$ ,  $((s, x), (s', x')) \in \mathcal{R}$  implies,

- for any  $a \in L$  if  $(s, x) \xrightarrow{a} (t, y)$ , then there exists  $t', y'$  such that  $(s', x') \xrightarrow{a} (t', y')$  and  $((t, y), (t', y')) \in \mathcal{R}$ ,
- for any  $t \in \mathbb{R}_0^+$  if  $(s, x) \xrightarrow{T_t} (t, y)$ , then there exists  $t', y'$  such that  $(s', x') \xrightarrow{T'_t} (t', y')$  and  $((t, y), (t', y')) \in \mathcal{R}$
- Vice-versa.

We say that two hybrid systems  $H$  and  $H'$  are *bisimilar* if there exists a bisimulation relation  $\mathcal{R} \subseteq Q \times Q'$  such that for all  $x \in Inv_i$  (recall  $i$  is the initial state of  $T$ ), there exists an  $x' \in Inv'_{i'}$  with  $((i, x), (i', x')) \in \mathcal{R}$  and vice-versa.

The main theorem below shows that the intuitive definition for hybrid system bisimilarity is captured by the abstract bisimulation (**P**-bisimilarity).

**Theorem 48** *Let  $H$  and  $H'$  be hybrid systems. Then  $H$  and  $H'$  are bisimilar iff they are **P**-bisimilar.*

**PROOF.** Suppose  $H$  and  $H'$  are  $\mathbf{P}$ -bisimilar, let the span be  $f : \tilde{H} \rightarrow H$  and  $g : \tilde{H} \rightarrow H'$ . We define a relation  $\mathcal{R} = (R^1, \{R_{s,s'}^2\}_{(s,s') \in R^1})$  as follows:

$$R^1 = \text{graph}(g^1) \circ \overline{\text{graph}(f^1)} \subseteq S \times S'$$

For  $(s, s') \in R^1$ , define

$$R_{s,s'}^2 = \bigsqcup_{\tilde{s}, f^1(\tilde{s})=s, g^1(\tilde{s})=s'} \text{graph}(g_{\tilde{s}}^2) \circ \overline{\text{graph}(f_{\tilde{s}}^2)}$$

Note that  $R_{s,s'}^2 \subseteq M_{f^1(\tilde{s})} \times M'_{g^1(\tilde{s})} = M_s \times M'_{s'}$ .

Regularity of  $R_{s,s'}^2$  follows from Proposition 23 and the fact that the disjoint union of regular relations is regular.

It remains to show that  $\mathcal{R}$  thus defined is a bisimulation relation, but this follows from  $f, g$  being  $\mathbf{P}$ -open surjective submersions.

Conversely, suppose  $H$  and  $H'$  are bisimilar, let the bisimulation relation be  $\mathcal{R} = (R^1, R_{s,s'}^2)$ , define a hybrid system  $\tilde{H} = (\tilde{T}, \tilde{X}, \tilde{Inv}, \tilde{G}, \tilde{R})$  as follows:

- $\tilde{T} = (T \times T')|_{R^1}$  which means that we remove all states of  $T \times T'$  not in  $R^1$ , we also remove the incident transitions on these states.
- For  $\tilde{s} = (s, s') \in R^1$ , define  $\tilde{X}_{\tilde{s}} : R_{s,s'}^2 \rightarrow TR_{s,s'}^2$  by  $\tilde{X}_{\tilde{s}} = (X_s \times X'_{s'})|_{R_{s,s'}^2}$ , this is well-defined by Theorem 25. Finally, we define
- $\tilde{Inv}_{(s,s')} = (Inv_s \times Inv'_{s'})|_{R_{s,s'}^2}$ ,  $\tilde{G}_{(s,s'),a} = (G_{s,a} \times G'_{s',a})|_{R_{s,s'}^2}$  and  $\tilde{R}_{(s,s'),a}$  is obtained from  $R_{s,a} \times R'_{s',a}$  by restricting its domain to  $R_{s,s'}^2$  and its range to  $R_{t,t'}^2$ , where  $(s, a, t), (s', a, t') \in \rightarrow$ .

The maps  $f : \tilde{H} \rightarrow H$  and  $g : \tilde{H} \rightarrow H'$  are defined using the projection maps on the discrete and continuous parts and can be shown to be  $\mathbf{P}$ -open surjective submersions. The proof is essentially similar to that of Theorem 25. Hence we have a span of  $\mathbf{P}$ -open surjective submersions  $(\tilde{H}, f, g)$  and  $H$  and  $H'$  are  $\mathbf{P}$ -bisimilar. □

## 7 Related Work

In this section we compare several aspects of our work with the existing ones in the literature.

## 7.1 Categorical approaches to modelling of hybrid systems

As much as the authors are aware the only other work that discusses categorical models of hybrid systems is the paper [16]. In this work, the authors construct an institution of hybrid systems and provide a categorical characterization of free aggregation, restriction and abstraction of such systems, thus providing a basis for compositional specification and verification of hybrid systems. However, they do not discuss bisimulations. More explicitly, they show that in the category of hybrid systems free aggregation corresponds to a product, restriction to a cartesian lifting and abstraction to a cocartesian lifting. Categorically inspired modeling of heterogeneous systems, consisting of multiple models of computation, is the primary concern of the tagged-signal model in [15], and more, recently, the trace algebraic framework in [4]

## 7.2 Categorical approaches to bisimulation

There has been considerable amount of research on categorical formulations of bisimulation in addition to [10]. We will be more specific on coalgebraic approach to bisimulation. See [21] for coalgebraic approaches to systems theory in general.

Coalgebraic formulation has been used successfully to model a variety of systems that include, deterministic systems, deterministic and nondeterministic labelled transition systems, supervisory control systems [13], symbolic dynamical systems, to name a few. More explicitly a labelled transition system  $(S, i, L, \rightarrow)$  defined in Section 3 can be viewed as an  $F$ -system  $(S, \alpha_S)$  with  $F : \mathbf{Set} \rightarrow \mathbf{Set}$  a functor and  $F(X) = 2^{L \times X}$  for any set  $X$ . Here  $\alpha_S : S \rightarrow F(S)$  is given by  $\alpha_S(s) = \{(a, s') \mid s \xrightarrow{a} s'\}$ . An  $F$ -homomorphism  $f : (S, \alpha_S) \rightarrow (T, \alpha_T)$  is a map  $f : S \rightarrow T$  such that  $F(f)\alpha_S = \alpha_T f$  which means that  $f$  both preserves and reflects the transition structure. This fact that a homomorphism reflects  $F$ -transitions makes it different from the morphisms we have in the category  $T_{\mathbf{L}}$ . Now suppose  $F : \mathbf{Set} \rightarrow \mathbf{Set}$  is a functor, and  $(S, \alpha_S)$  and  $(T, \alpha_T)$  are  $F$ -systems, a relation  $R \subseteq S \times T$  is said to be a bisimulation between  $S$  and  $T$  if there exists an  $F$ -dynamics  $\alpha_R : R \rightarrow F(R)$  such that the projections from  $R$  to  $S$  and  $T$  are  $F$ -homomorphisms.

Note that in the case of dynamical systems we have a functor, the so called tangent functor  $T : \mathbf{Man} \rightarrow \mathbf{Man}$ , and one is tempted to view a dynamical system  $X$  on a manifold  $M$  as a coalgebra  $(M, X)$  with  $X : M \rightarrow TM$ . However, this is not the case at the face of it, recall that a dynamical system is  $X : M \rightarrow TM$  such that  $\pi_M X = id_M$  where  $\pi_M$  is the canonical projection. On the other hand, clearly one could work in a full subcategory of  $\mathbf{coAlg}_T$



where the commutativity property is also satisfied.

On a more essential note, our choice to work with path objects and path categories instead of coalgebraic approach was due to the fact that in coalgebraic approaches one does not have a direct way of modelling the notion of time and trajectory for the system under study. However, in path object approach the flow of the system is made explicit and the notion of abstract bisimulation has the trajectories built into the definition through the  $\mathbf{P}$ -open maps. As a matter of fact in trying to formulate a notion of bisimulation for dynamical and especially for hybrid systems we have benefited greatly from having to first define a path object. This gave us an idea as to what the abstract notion of time should be for a hybrid system. As the reader might recall this is a tree with a single branch with bubbles on every state representing clocks working at constant rate 1.

## 8 Conclusions

In this paper, we developed novel notions of system equivalence for dynamical and control systems, unified the notion of bisimulation across discrete and continuous domains, developed bisimulation notions for hybrid dynamical systems. In all cases, proved that this definition is captured by the abstract bisimulation framework introduced in [10].

There are several future research directions, on the one hand there is the well known connection between abstract bisimulation, and logic and game characterizations of bisimulation and presheaf semantics in the case of concurrency models [27]. This direction can be exploited for dynamical and hybrid dynamical systems and in this way one obtains specification logics for such systems. We are very keen on further exploring the relation between our models and presheaf semantics.

On the other hand we have to further investigate the use and appropriateness of the notion of bisimulation for dynamical and hybrid systems in the context of real life engineering applications. The first step in this direction is to find algebraic characterizations of bisimulation for hybrid systems or for at least a class of such systems and hence make a step forward towards computability issues of such relations. Secondly, our definition might be too strong for applications, notice that the two bisimilar hybrid systems are locked in timing, that is wherever one gets in time  $t$  the other should also be able to simulate in the same time duration  $t$ . This condition could be weakened to allow for other equivalence relations similar to weak bisimulation relation in the context of concurrency theory [17]. Another weaker relation could be obtained by allowing a discrete transition  $a$  in one hybrid systems to be simulated by

pre and post time evolution of the other machine during the execution of the event  $a$ . We plan to study both of these weaker versions of equivalences and the possibilities of characterizing them in abstract bisimulation framework.

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## A Differential Geometry

Our treatment of differential geometry follows that of [8]. For a more thorough introduction to geometry, the reader may wish to consult numerous books on the subject such as [1,23].

### A.1 Differentiable Manifolds

Recall that a function  $h : A \rightarrow B$  is a homeomorphism iff  $h$  is a bijection and both  $h$  and  $h^{-1}$  are continuous. In this case, topological spaces  $A$  and  $B$  are called homeomorphic. A function  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  is called smooth or  $C^\infty$  if all derivatives of any order exist and are continuous. Function  $f$  is real analytic or  $C^\omega$ , if it is  $C^\infty$  and for each  $x \in \mathbb{R}^n$  there exists a neighborhood  $U$  of  $x$ , such that the Taylor series expansion of  $f$  at  $x$  converges to  $f(x)$  for all  $x \in U$ . A mapping  $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$  is a collection  $(f_1, \dots, f_m)$  of functions  $f_i : \mathbb{R}^n \rightarrow \mathbb{R}$ . The mapping  $f$  is smooth (analytic) if all functions  $f_i$  are smooth (analytic).

**Definition 49 (Manifolds)** *A manifold  $M$  of dimension  $n$  is a Hausdorff and second countable topological space which is locally homeomorphic to  $\mathbb{R}^n$ .*

A manifold, which is of great interest to us, is  $\mathbb{R}^n$  itself. A subset  $N$  of a manifold  $M$  which is itself a manifold is called a submanifold of  $M$ . Any open subset  $N$  of a manifold  $M$  is clearly a submanifold, since if  $M$  is locally homeomorphic to  $\mathbb{R}^n$  then so is  $N$ . In particular, an open interval  $I \subseteq \mathbb{R}$  is also a manifold.

A coordinate chart on a manifold  $M$  is a pair  $(U, \phi)$  where  $U$  is an open set of  $M$  and  $\phi$  is a homeomorphism of  $U$  on an open set of  $\mathbb{R}^n$ . The function  $\phi$  is also called a coordinate function and can also be written as  $(\phi_1, \dots, \phi_n)$  where  $\phi_i : M \rightarrow \mathbb{R}$ . If  $p \in U$  then

$\phi(p) = (\phi_1(p), \dots, \phi_n(p))$  is called the set of local coordinates in the chart  $(U, \phi)$ .

When doing operations on a manifold, we must ensure that our results are consistent regardless of the particular chart we use. We must therefore impose some conditions. Two charts  $(U, \phi)$  and  $(V, \psi)$  with  $U \cap V \neq \emptyset$ , are called  $C^\infty$  ( $C^\omega$ ) compatible if the map

$$\psi \circ \phi^{-1} : \phi(U \cap V) \subseteq \mathbb{R}^n \rightarrow \psi(U \cap V) \subseteq \mathbb{R}^n$$

is a  $C^\infty$  ( $C^\omega$ ) function. A  $C^\infty$  ( $C^\omega$ ) atlas on a manifold  $M$  is a collection of charts  $(U_\alpha, \phi_\alpha)$  with  $\alpha \in A$  which are  $C^\infty$  ( $C^\omega$ ) compatible and such that

the open sets  $U_\alpha$  cover the manifold  $M$ , so  $M = \bigcup_{\alpha \in A} U_\alpha$ . An atlas is called maximal if it is not contained in any other atlas.

**Definition 50 (Differentiable Manifolds)** *A differentiable (analytic) manifold is a manifold with a maximal,  $C^\infty$  ( $C^\omega$ ) atlas.*

Now that we have imposed this differential structure on our manifold  $M$  we can perform calculus on  $M$ . In particular let  $f : M \rightarrow \mathbb{R}$  be a map. If  $(U, \phi)$  is a chart on  $M$  then the function

$$\hat{f} = f \circ \phi^{-1} : \phi(U) \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$$

is called the local representative of  $f$  in the chart  $(U, \phi)$ . We therefore define the map  $f$  to be smooth (analytic) if its local representative  $\hat{f}$  is smooth (analytic). Notice if  $f$  is smooth (analytic) in one chart, then it is smooth (analytic) in every chart since we required our charts to be  $C^\infty$  ( $C^\omega$ ) compatible and our atlas to be maximal. Hence our results are intrinsic to the manifold and do not depend on the particular chart we use. Similarly, if we have a map  $f : M \rightarrow N$ , where  $M, N$  are differentiable manifolds, the local representation of  $f$  given a chart  $(U, \phi)$  of  $M$  and  $(V, \psi)$  of  $N$  is

$$\hat{f} = \psi \circ f \circ \phi^{-1}$$

which makes sense only if  $f(U) \cap V \neq \emptyset$ . Again  $f$  is smooth (analytic) if  $\hat{f}$  is a smooth (analytic) map.

## A.2 Tangent Spaces

Let  $p$  be a point on a manifold  $M$  and let  $C^\infty(p)$  denote the vector space of all smooth functions in a neighborhood of  $p$ . A tangent vector  $X_p$  at  $p \in M$  is an operator from  $C^\infty(p)$  to  $\mathbb{R}$  which satisfies for  $f, g \in C^\infty(p)$  and  $a, b \in \mathbb{R}$ , the following properties,

- (1) Linearity  $X_p(a \cdot f + b \cdot g) = a \cdot X_p(f) + b \cdot X_p(g)$
- (2) Derivation  $X_p(f \cdot g) = f(p) \cdot X_p(g) + X_p(f) \cdot g(p)$

The set of all tangent vectors at  $p \in M$  is called the tangent space of  $M$  at  $p$  and is denoted by  $T_p M$ . The tangent space  $T_p M$  becomes a vector space over  $\mathbb{R}$  if for tangent vectors  $X_p, Y_p$  and real numbers  $c_1, c_2$  we define

$$(c_1 \cdot X_p + c_2 \cdot Y_p)(f) = c_1 \cdot X_p(f) + c_2 \cdot Y_p(f)$$

for any smooth function  $f$  in the neighborhood of  $p$ . The collection of all tangent spaces of the manifold,

$$TM = \bigcup_{p \in M} T_p M$$

is called the tangent bundle. The tangent bundle has a naturally associated projection map  $\pi : TM \rightarrow M$  taking a tangent vector  $X_p \in T_p M \subset TM$  to the point  $p \in M$ . The tangent space  $T_p M$  can then be thought of as  $\pi^{-1}(p)$ .

The tangent space can be thought of as a special case of a more general mathematical object called a fiber bundle. Loosely speaking, a fiber bundle can be thought of as gluing sets at each point of the manifold in a smooth way.

The tangent bundle is a vector bundle and the fiber at each point  $p \in M$  is the tangent space  $T_p M$ . In particular, the tangent bundle  $TM$  has dimension  $2n$ , where  $M$  is  $n$ -dimensional.

Now let  $M$  be a manifold and let  $(U, \phi)$  be a chart containing the point  $p$ . In this chart we can associate the following tangent vectors

$$\frac{\partial}{\partial \phi_1}, \dots, \frac{\partial}{\partial \phi_n}$$

defined by

$$\frac{\partial}{\partial \phi_i}(f) = \frac{\partial(f \circ \phi^{-1})}{\partial x_i}$$

for any smooth function  $f \in C^\infty(p)$ . The tangent space  $T_p M$  is an  $n$ -dimensional vector space and if  $(U, \phi)$  is a local chart around  $p$  then the tangent vectors

$$\frac{\partial}{\partial \phi_1}, \dots, \frac{\partial}{\partial \phi_n}$$

form a basis for  $T_p M$ . Therefore if  $X_p$  is a tangent vector at  $p$  then

$$X_p = \sum_{i=1}^n a_i \frac{\partial}{\partial \phi_i}$$

where  $a_1, \dots, a_n$  are real numbers. From the above formula we can see that  $X_p(f)$  is an operator which simply takes the directional derivative of  $f$  in the direction of  $[a_1, \dots, a_n]$ .

Now let  $M$  and  $N$  be smooth manifolds and  $f : M \rightarrow N$  be a smooth map. Let  $p \in M$  and let  $q = f(p) \in N$ . We wish to push forward tangent vectors from  $T_p M$  to  $T_q N$  using the map  $f$ . The natural way to do this is by defining a map  $T_p f : T_p M \rightarrow T_q N$  by

$$(T_p f(X_p))(g) = X_p(g \circ f)$$

for smooth functions  $g$  in the neighborhood of  $q$ . One can easily check that  $T_p f(X_p)$  is a linear operator and a derivation and thus a tangent vector. The map  $T_p f : T_p M \rightarrow T_{f(p)} N$  is called the push forward map of  $f$ . The push forward map  $T_p f : T_p M \rightarrow T_{f(p)} N$  is a linear map, and furthermore if  $f : M \rightarrow N$  and  $g : N \rightarrow K$  then

$$T_p(g \circ f) = T_p g \circ T_p f$$

which is essentially the chain rule.

### A.3 Vector Fields

A vector field on a manifold  $M$  is a smooth map  $X$  which places at each point  $p$  of  $M$  a tangent vector from  $T_p M$ . Therefore since a vector field,  $X$ , places at each point  $p$  a tangent vector  $X(p)$  we have that in the chart  $(U, \phi)$  the local expression for the vector field  $X$  is

$$X(p) = \sum_{i=1}^n a_i(p) \frac{\partial}{\partial \phi_i}$$

The vector field is smooth (analytic) if and only if  $a_i(p)$  is  $C^\infty$  ( $C^\omega$ ).

Let  $I \subseteq \mathbb{R}$  be an open interval containing the origin. An integral curve of a vector field is a curve  $c : I \rightarrow M$  whose tangent at each point is identically equal to the vector field at that point. Therefore an integral curve satisfies for all  $t \in I$ ,

$$c' = T_t c(t, 1) = X(c)$$

A vector field is called complete if the integral curve passing through every  $p \in M$  can be extended for all time, that is we can choose  $I = \mathbb{R}$ . Integral curves of smooth (analytic) vector fields are smooth (analytic).

**Definition 51 ( $f$ -related Vector Fields)** *Let  $X$  and  $Y$  be vector fields on manifolds  $M$  and  $N$  respectively and  $f : M \rightarrow N$  be a smooth map. Then  $X$  and  $Y$  are  $f$ -related iff*

$$T(f) \circ X = Y \circ f. \tag{A.1}$$

If  $f$  is not surjective, then  $X$  may be  $f$ -related to many vector fields on  $N$ . If, however,  $f$  is surjective, then  $X$  can only be  $f$ -related to a unique vector field on  $N$ .