Modelling Concurrent Systems Notes

Leon Lee

November 5, 2024

Contents

1 Introduction to Concurrent Systems

1.1 Lecture 1 - Specification and Implementation

The main topics that are covered in this course:

- Formalising specifications as well as implementations of concurrent systems
- Studying the criteria for deciding whether an implementation meets a specification
- Techniques for proving whether an implementation meets a specification

Both specifications and implementations can be represented by means of **models of concurrency** such as **Labelled Transition Systems (LTSs)** or **Process Graphs**.

Definition 1.1.1: Process Graphs and LTSs

A **process graph** is a triple $(S, I, \rightarrow)$, defined by the following:

- S is a set of **states**
- $I \in S$ is an **initial state**
- $\rightarrow$ is a set of triples (s, a, t) with $s, t \in S$, and a an **action** drawn from a set `Act`

A **Labelled Transition System(LTS)** is a *process graph* without the initial state (but sometimes LTS is used as a synonym for process graph i.e. with the initial state)

Sometimes we will use process graphs with a fourth component $\checkmark \subseteq S$ indicating the **final** states of the process: those in the system can terminate successfully

Specifications and implementations can not only be represented by LTSs or other models of concurrency, but also by **process algebraic expressions**, where complex processes are built up from constants for atomic actions using operators for *sequential*, *alternative*, and *parallel composition.*
The most popular process algebraic languages from literature are:

- **CCS**: the Calculus of Communicating Systems
- **CSP**: Communicating Sequential Processes
- **ACP**: the Algebra of Communicating Processing

We will be using ACP, focusing on the *partially synchronous parallel composition* operator

Definition 1.1.2: ACP

The syntax of **ACP**, the **Algebra of Communicating Processes** features the operations

1. ϵ: **Successful termination** (only in the optional extension ACP_ϵ)
2. δ: **Deadlock**
3. a: **Action constant** for each action a
4. $P \cdot Q$: **Sequential Composition**
5. $P + Q$: **Summation**, **Choice**, or **Alternative Composition**
6. $P||Q$: **Parallel Composition**
7. $\partial_H(P)$: **Restriction**, or **Encapsulation** for each set of visible actions H
8. $\tau_I(P)$: **Abstraction** for each set of visible actions I (only in the optional extension ACT_τ)

Note: There is also left and right parallel operators, P
The atomic actions of ACP consist of all a, b, c etc from a given set A of visible actions, and one special action τ, that is meant to be internal and invisible to the outside world.
For each application, a partial **communication function** $\gamma : A \times A \to A$ is chosen that tells for each two visible actions a and b whether they synchronise (namely if γ is defined), and if so, what is result of their synchronisation: $\gamma(a, b)$. The communication function is required to be commutative and associative. The invisible action cannot take part in synchronisations.

Definition 1.1.3: ACP in terms of Process Graphs

Below is the **ACP** operations in terms of process graphs extended with a predicate ✓ that signals successful termination

- ϵ is the graph with one state and no transition. This one state is the initial state, and is marked with ✓
- δ is the graph with one state and no transitions. This one state is the initial state. It is not makred as terminating.
- a is a graph with two states (and initial and a final one) and one transition between them, labelled a. The final state is marked with ✓
- $G \cdot H$ is the process that first performs G, and upon successful termination of G proceed with H.
- $G + H$ is obtained by taking the union of copies of G and H with disjoint sets of states, and adding a fresh state **root** which will be the initial state of $G + H$. For each transition $I_G \xrightarrow{a} s$ in G, where I_G denotes the initial state of G, there will be an extra transition **root** $\xrightarrow{a} s$, and likewise, for each transition $I_H \xrightarrow{a} s$ in H, where I_H denotes the initial state of h, there will be an extra transition **root** $\xrightarrow{a} s$

  root is labelled with ✓ if either I_G or I_H is.
- $G||H$ is obtained by taking the Cartesian product of the states of G and H; that is, the states of $G|H$ are pairs (s, t) with s a state from G and t a state from H. The initial state of $G||H$ is the pair of initial states of G and H. A state (s, t) is labelled ✓ iff both s and t are labelled ✓. The transitions are
  - $(s, t) \xrightarrow{a} (s', t)$ whenever $s \xrightarrow{a} s'$ is a transition in G
  - $(s, t) \xrightarrow{a} (s, t')$ whenever $t \xrightarrow{a} t'$ is a transition in H
  - $(s, t) \xrightarrow{c} (s', t')$ whenever $s \xrightarrow{a} s$ is a transition in G, and $t \xrightarrow{b} t'$ is a transition in H, and $\gamma(a, b) = c$

  Intuitively, $G||H$ allows all possible interleavings of actions from G and actions from H. In addition, it enables actions to synchronise with their communication partners.
- $\partial_H(G)$ is just G, but with all actions in G omitted. It is used to remove the remnants of unsuccessful commmunication, so that the synchronisation that is enabled by parallel composition, is enforced.
- $\tau_I(G)$ is just G, but with all actions in I renamed into τ.

These semantics are of the **denotional** kind. Here ”denotional” entails that each constant denotes a process graph (up to **isomorphism**) and each ACP operator denotes an operation on process graphs (creating a new graph out of one or two argument graphs)

1.2 Deadlocks

Deadlock means that a process isn't "terminated" but it cannot go further
ACP-ϵ is an alternative modele where non-finishing states can also terminate

1.3 Relations

Definition 1.3.1: Equivalence Relation

A binary relation $\sim$ on a set D is an **equivalence relation** if it is

- **Reflexive**: $p \sim p$ for all processes $p \in D$
- **Symmetric**: If $p \sim q$ then $q \sim p$
- **Transitive**: If $p \sim q$ and $q \sim r$ then $p \sim r$

Definition 1.3.2: Equivalence Class

If $\sim$ is an equivalence relation on D, and p is in D, then $[p]_{\sim}$ denotes the set of all processes in D that are equivalent to p. Such a set is called an **equivalent class**

Equivalence relations that split a set into more sets are called **finer** or **more discriminating**, and equivalence relations that split a set into less sets are called **coarser** or **more identifying**. The finest relation is e - every element has its own class, and the coarsest relation is the universal equivalence - everything is equivalent to itself

Definition 1.3.3: Equivalence Relation

A binary relation on a set D is a **preorder** ($\sqsubseteq$) if it is

- **Reflexive**: $p \sqsubseteq p$ for all processes $p \in D$
- **Transitive**: If $p \sqsubseteq q$ and $q \sqsubseteq r$ then $p \sqsubseteq r$

1.4 Reactive Systems

2 CCS

3 Congruence Closure

3.1

Definition 3.1.1: Congruence Closure

For an equivalence $\sim$, we have $\sim^c$, its congruence closure where

$$P \sim^c Q \implies \forall C[], C[P] \sim C[Q]$$

$$\begin{tikzcd}
B & & & \\
& & BB^C \arrow[ull] & \\
& & WB^C \arrow[u] & BB \arrow[ul] \\
& & & WB \arrow[ul] \arrow[u] \\
CT^C \arrow[uuuu] & & & \\
CT^\infty \arrow[u] & & & \\
& & & CT^* \arrow[ulll] \arrow[uuu]
\end{tikzcd}$$

3.1.2 Showing Congruences

Example: Show that $=_{PT}$ is a congruence for ∂_H

$$P =_{PT} Q \implies \partial_H(P) =_{PT} \partial_H(Q)$$

WTS

$$PT(P) = PT(Q) \implies PT(\partial_H(P)) = PT(\partial_H(Q))$$

$$PT(\partial_H(P)) = \{\sigma \in PT(P) \mid \sigma \text{ does not contain any action from } H\}$$

We can just replace $PT(P)$ with $PT(Q)$ and the implication follows automatically
Example: Show that $=_{CT}$ is **not** a congruence for ∂_H
For $P = ab + ac$, we have $CT(\partial_b(P)) = a + ac$
For $Q = a(b + c)$, we have $CT(\partial_b(Q)) = ac$

3.2 Equational Logic

Equations - of the form $P = Q$
Equational logic - comprised of axioms, and rules
Rules use the rules listed below

- Reflexive: $P = P$
- Symmetric: $P = Q$ and $Q = P$
- Transitive: $P = Q$ and $Q = R$ implies $P = R$

- Substitution: $P = P + P$ implies $a.b = a.b + a.b$
- Congruence: $P = Q \implies C[P] = C[Q]$

$$Ax \vdash P = Q \text{ if } P = Q \text{ follows from the ...}$$

Theorem 3.2.1

$$P =_B Q \iff Ax \vdash P = Q$$

You want proofs to be sound and complete
Operations of the + in CCS

- $P + Q = Q + P$
- $(P + Q) + R = R + (Q + R)$
- $P + P = P$
- $P + 0 = P$

Operations of $P|Q$:

$$P = \sum_{i=1}^{k} a_i P_i = a_1 P_1 + a_2 P_2 + \cdots + a_k P_k$$

$$Q = \sum_{j=1}^{l} b_j Q_j$$

Theorem 3.2.2: Expansion Law

$$P|Q = \sum_{i=1}^{k} a_i.(P_i|Q) + \sum_{j=1}^{l} b_j.(P|Q_j) + \underbrace{\sum_{i=1}^{k}\sum_{j=1}^{l}}_{(a_i = \bar{b}_j)} \tau(P_i|Q_j)$$

$$\gamma : A \times A \to (A \uplus \{\delta\})$$

$\gamma(a_i, b_j) = \delta$ if they do not communicate

Definition 3.2.3: Head normal form

Something is in head normal form if it can be written in the form

$$P = \sum a_i.P_i$$

Example: We can write

$$\begin{aligned}(a.b|c) &= a(b|c) + c(a.b)\\ &= a(bc + cb) + c(a.b)\end{aligned}$$

Example: $\partial_H(P + Q) = \partial_H(P) + \partial_H(Q)$

3.3 General Structural Operational Semantics

$$\frac{x \to w}{f(x, y, z) \to g(h(v, w))}$$

3.4 Hennessy-Milner Logic

HML is a set of formulas in the following syntax:

$$\phi ::= \top \mid \bot \mid \phi_1 \wedge \phi_2 \mid \phi_1 \vee \phi_2 \mid \neg\phi \mid \langle a \rangle \phi \mid [a]\phi$$

- $P \models \phi$: "Process P satisfies formula ϕ if ϕ holds for P"
- $P \models \langle a \rangle \phi$: iff there is a P' such that $P \xrightarrow{a} P'$ and $P \models \phi$
- $P \models [a]\phi$ iff for all $P \xrightarrow{a} P'$ we have $P' \models \phi$

3.5 Safety

Definition 3.5.1: Canonical Safety Property

A process p satisfies the **canonical safety property**, notation $P \models \text{safety}(b)$ if no trace of P contains the action b

$$P \models \text{safety}(B) \iff PT(P) \cup B = \emptyset$$

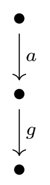
Definition 3.5.2: Safety Equivalence

P is a safety equivalence to Q if for all safety properties, if $P \models \text{safety}(B)$ then so does Q

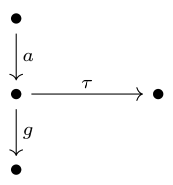
Theorem 3.5.3

$$P \equiv_{\text{safety}} Q \iff P =_{PT} Q$$

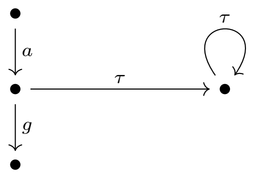
$$P \sqsubseteq Q \iff PT(Q) \subseteq PT(P)$$



normal process

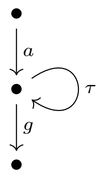


Deadlock



Livelock Divergent

NotBBE



Escapable Divergence