Formal methods: Lecture 2

11.02.2015

Model Checking I:

TRANSITION SYSTEMS

Model Checking (MC) problem: intuition

- Correct design means that certain correctness properties must be satisfied by the system to be developed
- Correctness properties state what behaviours/features are correct and what are not in the system.
- To apply rigorous verification methods both
  - system description and
  - correctness properties description

  must be formalised
- System is described formally with its *model*
- Properties are specified formally as *logic expressions*.

Model Checking (formally)

- Satisfaction relation symbolically:

$$M \models \varphi \,?$$

"Does model *M* satisfy logic expression φ ?"

- Property φ is stated often in temporal logic
- *M* is a state-transition system that models the behavior of the implementation to be verified

Procedural view:

- Model checking is an enumeration method of the state space of *M* to determine if it satisfies the property φ.

Advantage of MC

- Fully automatic
- Diagnostic trace (counter example) generated by checker helps to analyze the source of the problem
- Good for bug-hunting, i.e a “debugger” that does not require full execution of your program.

Modelling

How to get *M*?

1. By the process of abstraction:
   - Makes verification possible by retaining the part of the system that is relevant to modeling;
   - Should not discard too much so that the result lacks certainty, or too little so that the verification is not feasible;
   - Usually done by human (novel automatic model extraction techniques are gaining popularity).
2. By observation and learning (model learning)

Choice of models

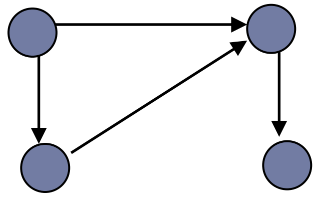
- We focus on state-transition systems. They are
  - acceptable by model checkers;
  - mostly finite set of states and transitions;
  - also push-down automata/systems are possible;
  - source programs can also be used as models, e.g., Pathfinder for Java code;
  - in symbolic encoding the logic formula specify abstract properties instead of explicit state behavior modelling.

Modeling notions

- State
  - We want to express what is true in a particular state
  - A *state* is a "snapshot" of the system variables' valuation(s).

- Transition represents relation between states.

  Can be an abstraction of

  - **C program** statement, e.g. *x++;*
  - an electronic circuit
  - or just an arrow, the source and destination states of which matter.

Atomicity

- Atomic transition – uninterruptable when started
- Atomicity determines the abstraction level of the model
  - too big step may miss intermediate states that are relevant;
  - too small step may blow up the model unnecessarily.
- Atomicity of transitions must consider concurrency
  - possible interleavings of transitions and interactions must be explicit.

Kripke Structure (*KS*)

One of the classical STSs

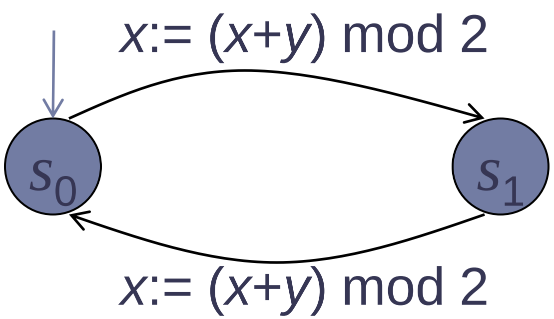
4-tuple (S, S_0, L, R) over a set of atomic propositions AP where

- S is a set of (control) states
- S_0 is initial state
- L is a labeling function: $S \rightarrow 2^{AP}$
- R is the transition relation: S x S

Example of *KS*

Assume in s_0 x=1 and y=1

- $S = \{s_0, s_1\}$
- $S_0 = \{s_0\}$
- $R = \{(s_0, s_1), (s_1, s_0)\}$
- $L(s_0) = \{x=1, y=1\}$
- $L(s_1) = \{x=0, y=1\}$



Modeling Reactive System

- Reactive systems:
  - do not terminate;
  - interact with their environment constantly;
  - *KS* is just one way of modeling them.
- Consider *KS* as a simple modeling language for RS-s.

Properties of reactive systems to verify

- *race condition* - the output depends on the sequence of uncontrollable events. It becomes a *bug* when events do not happen in the order the programmer intended, e.g.
  - in file systems, programs may "collide" in their attempts to modify or access a file, which could result in data corruption;
  - in networking, two users of different servers on different ends of the network try to start the same-named channel at the same time.
- *deadlock* – all processes are infinitely waiting after each other for releasing the resources. Generally undecidable, practical only for finite state processes.
- *starvation* - blocking resources for only some processes.
- etc.

Modeling Concurrent Programs with *KS*

- Steps of constructing KS from a program (by Manna, Pnueli):
    1. Abstract (sequential) component programs as logic relations.
    2. Compose the logic relations for the *concurrent program.*
    3. Compute a Kripke structure from the logic relations.

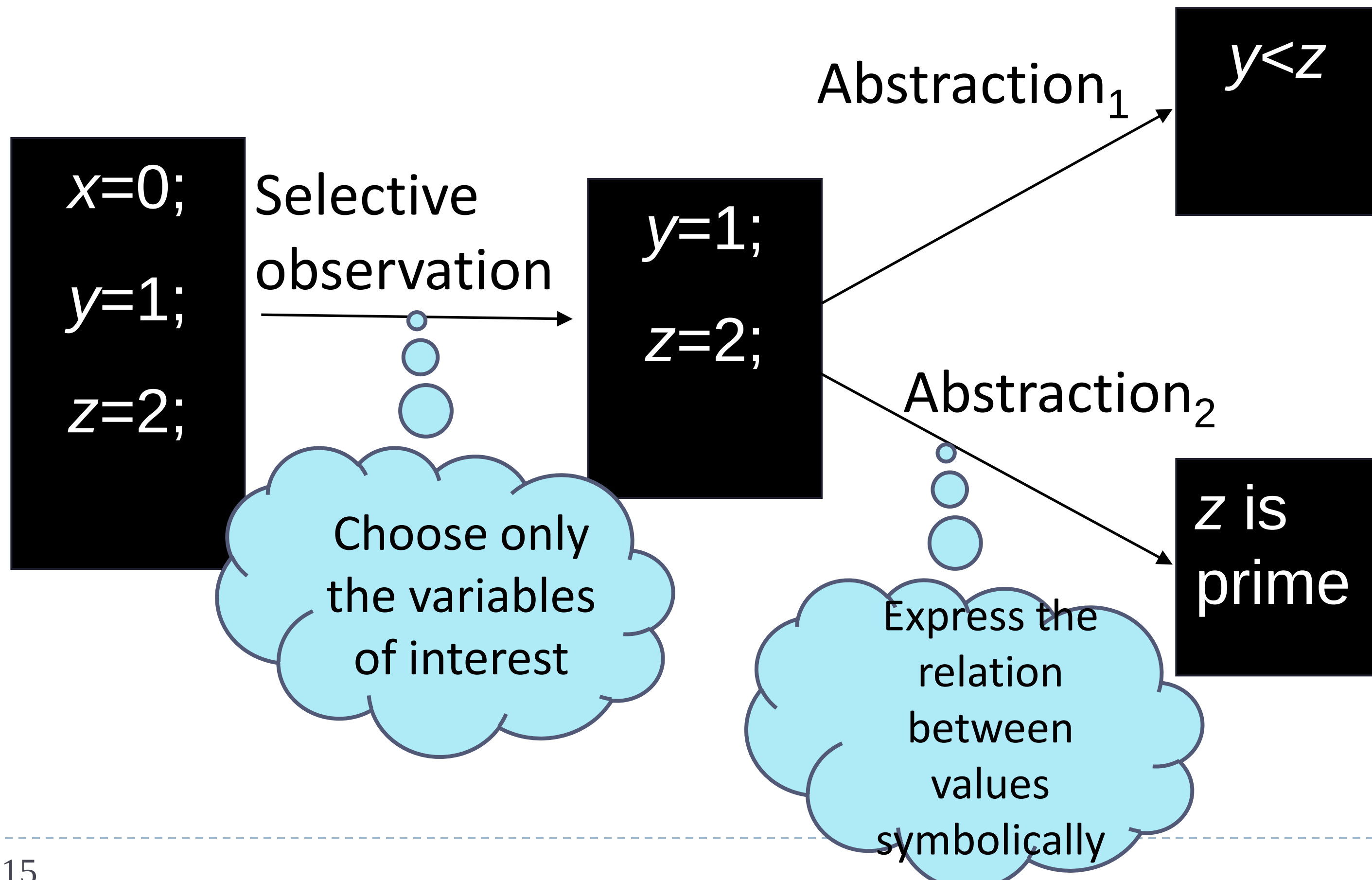
How it works in practice?

Describing States

For abstracting states we use program variables and 1st order predicate logic…

- true, false, ¬, ∧, ∨, ∀, ∃, →
- extended with equality "=" and interpreted predicate symbols and function symbols:
  - $x = y$
  - even (x)
  - odd (x)
  - prime (x)
    - etc

Example of state abstraction steps



Representing States

- *Valuation* of a state
  - A mapping: $V \rightarrow \boldsymbol{V}$ from observable state variables V to their value domain $\boldsymbol{V}$,
- *Symbolic state* = set of explicit states
  - the set of states is described by a 1st order logic formula
  - Instead of enumerating explicit states we use a logic formula describing the set S_0
  - Example: $S_0 \equiv (x = 1) \wedge (y > 2)$

Representing a transition

- Transition abstracts a program command (or circuit)
  - Distinguish two sets of variables' values:

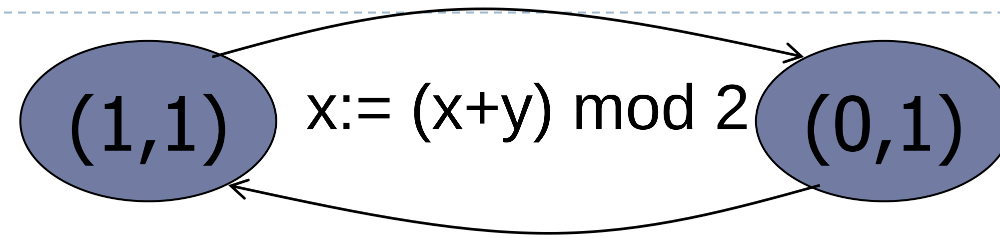
    V and *V'* for variable valuation in pre- and post-state of the transition, respectively
- Transition relation is a relation between *V* and *V'*
  - relation is expressable as a set of pairs of states
  - represented as a logic formula on *V*, *V'* with "=",
- Example:
  - Relation x' = x+1 describes the effect of program statement x:=x+1

From Logic Relation to Kripke Structure

Rules

- S (statespace) is the set of all valuations for V;
- S_0 is the set of all valuations that satisfy S_0 (a logic formula)
- If s and s' are two states, s.t. $(s,s') \in R(s,s')$ then the pair (s,s') is a transition in KS;
- L is defined so that $L(s)$ is the subset of all atomic propositions true in s.

Example



- $S_0 \equiv x = 1 \wedge y = 1$
- $R \equiv x' = (x+y) \bmod 2$
- $S = B \times B$, where $B = \{0,1\}$

- $S_0 = \{(1,1)\}$
- $R = \{((1,1), (0,1)), ((0,1),(1,1))\}$
- $L(1,1) = \{x=1, y=1\}$
- $L(0,1) = \{x=0, y=1\}$

Abstracting parallel programs to KS

- A parallel program contains sequential processes
  - with synchronization primitives: wait, lock and unlock
  - processes may share variables
  - no assumption about the speed and execution order of these processes
- Program commands are labeled by $l_1 \ldots l_n$
- We use $C(l_1, P, l_2)$ to denote the logic relation of the transition that represents program P.

How to compute transition relation for sequential program fragments?

- Base case: atomic statements:
  - skip   % has no effect on data variables
  - assignment: x := e

  Let *C* describe valuations before and after executing *P*: x := e

$C(l_1, \mathrm{x:=e}, l_2) \equiv$

$pc = l_1 \wedge pc' = l_2 \wedge x' = e \wedge \mathit{same}(V \setminus \{x\})$

  - $\mathit{same}(Y)$ means $y' = y$, for all $y \in Y$.

How to compute transition relation for sequential program fragments? (2)

- Sequential composition

  $C(l_0, P1 \; ; \; l: P2, l_1) = C(l_0, P1, l) \vee C(l, P2, l_1)$

- $C(l$, **if b then** l_1: P1 **else** l_2: P2 **end if**, $l')$ is the disjunction of:

Conditional part

- $pc = l \wedge pc' = l_1 \wedge b \wedge \mathit{same}(V)$
- $pc = l \wedge pc' = l_2 \wedge \neg b \wedge \mathit{same}(V)$

Body part

- $C(l_1, P1, l')$
- $C(l_2, P2, l')$

Example: concurrent while-loops sharing a variable “turn”

```
L0: while (true) do
  NC0: wait (turn =0);
  CR0: turn := 1;
  end while
L0’
```

```
L1: while (true) do
  NC1: wait (turn =1);
  CR1: turn := 0;
  end while
L1’
```

- identify variables, including program counters
- compute set of states and set of initial states
- compute transitions

Example (continued I)

```
L0: while (true) do
    NC0: wait (turn =0);
    CR0: turn := 1;
    end while
L0'
```

```
L1: while (true) do
    NC1: wait (turn =1);
    CR1: turn := 0;
    end while
L1'
```

Identify variables, including program counters:

- *V* = { pc_0, pc_1, turn}
- domain of **pc_0** is L0, NC0, CR0, L0'
- domain of **turn** is {0,1}

Example (continued II)

```
L0: while (true) do
    NC0: wait (turn =0);
    CR0: turn := 1;
    end while
L0'
```

```
L1: while (true) do
    NC1: wait (turn =1);
    CR1: turn := 0;
    end while
L1'
```

- Compute set of states and set of initial states
  - S= {(L0, L1, 1), (L0, L1, 0), (L0, NC1, 0), (L0, NC1, 1) …}
  - S_0 = {(L0, L1, 0), (L0, L1, 1)}

Example (continued III)

```
m: cobegin

L0: while (true) do
    NC0: wait (turn =0);
    CR0: turn := 1;
    end while
L0'

m': coend
```

- Compute transition relation separately & then compose them together:
  - For global program counter *dom*(pc) = {m, m', $\perp$}
  - $\perp$ represents that one of local pc is taking effect.

Example (continued IV)

```
m: cobegin

L0: while (true) do          L1: while (true) do
   NC0: wait (turn =0);         NC1: wait (turn =1);
   CR0: turn := 1;              CR1: turn := 0;
   end while                    end while
L0'                           L1'

m': coend
```

- Transition relations of the composition:

$C(L0, P0, L0') \equiv turn'=turn+1 \wedge \mathit{same}(V \setminus V0) \wedge \mathit{same}(PC \setminus PC0)$

Summary

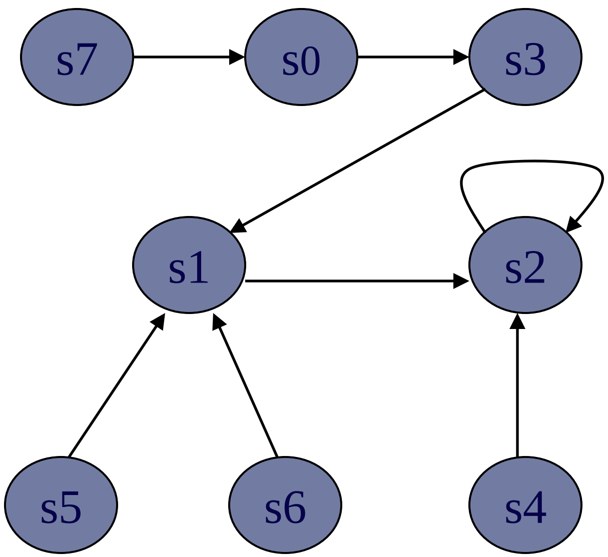
- Concept of MC (at very high level):
  - An automatic procedure that verifies temporal and state properties
  - Requires input:
    - a state transition system
    - a temporal property
- State transition system – Kripke structure (KS):
  - KS structure is our (teaching) language
  - *KS* models reactive systems
- An example demonstrated how a concurrent program is translated to *KS*:
  - Concurrent program to logic relations
  - Logic relations to *KS*.

Next lecture

- Temporal properties
  - CTL*, CTL and LTL
  - Their semantics
- CTL model checking on a Kripke structure

Exercise

- Give your definition of APs p, q, r.



L(s0) = {¬ p, ¬ q, ¬ r}
L(s1) = {¬ p, ¬ q, r}
L(s2) = {¬ p, q, ¬ r}
L(s3) = {¬ p, q, r}
L(s4) = {p, ¬ q, ¬ r}
L(s5) = {p, ¬ q, r}
L(s6) = {p, q, ¬ r}
L(s7) = {p, q, r}