Parallelism

Master 1 International

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Lecture 4

Theoretical Models

Table of Contents

Introduction

- Fundamental problems:
  - Primary: establishing the equivalence of programs
  - Secondary: proving other interesting properties
- A **model** provides an abstract view in which the “irrelevant” details are ignored in establishing the equivalence of systems
- A **denotational model** is one in which the meaning of a system can be derived from its constituent parts (compositionality)
- For sequential programming, computer scientists have been successful in building denotational models of programs which abstract away the *operational* details
- For concurrent programming, it is harder to come up with such models, mainly due to interleaving

Petri Nets

- Introduced by Carl Adam Petri
- A mathematical modeling language for the description of distributed systems
- A bipartite graph consisting of places, transitions, and arcs
- Places contain a discrete number of tokens.
- A distribution of tokens over the places is called a marking.
- A transition may fire whenever its input places contain sufficient tokens.
- Firing is atomic. Upon firing, a transition
  - consumes tokens in its input places
  - places tokens in its output places.
- Execution of Petri nets is nondeterministic

Petri Nets: Typical Interpretations

Input Places	Transition	Output Places
Preconditions	Event	Postcondition
Input data	Computation step	Output data
Input signals	Signal processor	Output signal
Resources needed	Task or job	Resources released
Conditions	Logical clause	Conclusion(s)
Buffers	Processor	Buffers

Petri Net: Formal Definition

- A Petri net is a 5-tuple $PN = (P, T, F, W, M_0)$ where:
  - $P = \{p_1, p_2, \ldots, p_m\}$ is a finite set of places,
  - $T = \{t_1, t_2, \ldots, t_m\}$ is a finite set of transitions,
  - $F \subseteq (P \times T) \cup (T \times P)$ is a set of arcs (flow relation),
  - $W : F \rightarrow \{1, 2, 3, \ldots\}$ is a weigh function,
  - $M_0 : P \rightarrow \{0, 1, 2, 3, \ldots\}$ is the initial marking,
  - $P \cap T = \emptyset$ and $P \cup T \neq \emptyset$.
- A Petri net structure $N = (P, T, F, W)$ without any specific initial marking is denoted by N
- A Petri net structure N with marking M is denoted (N, M)

Petri Nets: Behavioral Properties

- Reachability: M is reachable iff $\exists\ \sigma : M_0\ [\sigma > M$
  - $R(M_0)$ is the set of reachable markings
  - Reachability problem: decidable, but EXPSPACE
- Boundedness: no. of tokens in each place is bounded for any reachable marking; k-bounded: ≤ k; 1-bounded = safe
- Liveness: at any marking M, any transition may eventually fire
  - A transition is Lk-live if it may fire in k time steps (weaker)
- Reversibility: from any M it is possible to reach a home state M'
- Synchronic Distance between two transitions:
  - $d(t_1, t_2) = \max_\sigma | N_\sigma(t_1) - N_\sigma(t_2) |$, where $N_\sigma(t)$ = firings of t in σ

Actor Model

- A mathematical model of concurrent computation
- Proposed by Carl Hewitt in 1973
- Studied by Gul Agha in his PhD Thesis at MIT (1985)
- Actors are the universal primitives of parallel computation
- Actors = Processes
- Actors exchange messages asynchronously and create other actors
- Abstract actor machine with a minimal programming language
- To send a communication, an actor specifies the target
- Communications are buffered and eventually delivered
- Denotational semantics based on transitions

Simple Actor Language (SAL)

- <behavior definition> ::=
  def <beh name> (<acquaintance list>) [<communication list>]
  <command>*
  end def
- <parameter list> ::= {id | <var list> } | {, id | , <var list> } | ε
- <var list> ::= case <tag field> of <variant>+ end case
- <variant> ::= <label> : <parameter list>
- <command> ::= if <condition> then <command>
  { else <command> } fi |
  become <expression> | send <msg> to <target> |
  <let bindings> “{“ <command> “}” |
  <behavior definition> | <command>*

Denotational Semantics (1)

- Tasks: communications which are still pending (not yet accepted)
  task = (tag, target, msg = [value_1, value_2, …, value_n])
- Local states function l : target → behavior
- **configuration** of an actor system: c = (local states fn, tasks)
- Behavior : msg → (new tasks, new actors, replacement behavior)
- Actor = (mail address (= to be used as target), behavior)
- The behavior of an actor whose mail address is m is a function (tag, m, msg) → (set of tasks, set of actors, replacement actor)
- Depending on the incoming communication (tag, m, [v_1, …, v_n]), send communications to specified targets (1) creating new actors and (2) specifying a replacement actor machine

Denotational Semantics (2)

Task $\tau = (t, m, k)$

Transition: $c \xrightarrow{\tau} c'$

Configurations

$\tau \in \text{tasks}(c)$

$\text{states}(c)(m) = \beta$, where $\beta(t, m, k) = (T, A, \gamma)$

$\text{tasks}(c') = (\text{tasks}(c) - \{\text{tau}\}) \cup T$

$\text{states}(c') = (\text{states}(c') - \{(m, \beta)\}) \cup A \cup \{\gamma\}$

Subsequent transition: $c \overset{\tau}{\rightarrowtail} c'$

$\tau \in \text{tasks}(c) \wedge c \rightarrow^* c' \wedge \tau \notin \text{tasks}(c') \wedge$

$\quad \nexists c''(\tau \notin \text{tasks}(c'') \wedge c \rightarrow^* c'' \wedge c'' \rightarrow^* c')$

Actor Model

- The Actor Model provides solution to three central problems in distributed computing:
  - Divergence (= infinite loops), thanks to the “guarantee of mail delivery”
  - Deadlock (cf. “the five dining philosophers”)
    - No syntactic (= low-level) deadlock possible
    - Semantic deadlocks are possible, but may be detected
    - Solve detected deadlock by negotiation
  - Mutual exclusion: not really a problem for actors
    - An actor can be “accessed” only by sending it some mail
    - An actor accepts just one mail and specifies a replacement that will accept the next mail in queue

Problems of the Actor Model

- No direct notion of inheritance or hierarchy (not OO)
- Actors encompass the ideas of modularity and encapsulation though, because an actor is self contained and atomic
- The ability to create other actors can dramatically change the state of the system
- Behavior replacement: dynamic, hard to perform using a static language.
- Guarantee of delivery means unbounded mailboxes
- Asynchronous message passing may cause problems for certain algorithms/data structures (e.g., stack)
- Insensitive actors (waiting a reply before processing other msg's) hard to implement

Trace Theory

- Finite automata are a convenient model of sequential programs
- Automata admit powerful analysis tools
  - Structural properties: underlying graph-like model
  - Behavioral properties: formal language theory
- Basic idea: use well-developed tools from formal language theory for the analysis of concurrent systems
- A concurrent system is understood as in the theory of Petri nets
- The algebra of dependency graphs (such as Petri nets) is isomorphic to that of trace monoids
- Alternative to concurrency as interleaving non-determinism
- First formulated by Antoni Mazurkiewicz in the 1970s

Traces

- Loosely speaking, a trace is an equivalence class of strings which differ only in the ordering of adjacent independent symbols
- Dependency relation D: if a D b, then b D a and a D a;
  a $\equiv_D$ b iff ¬(a D b): symbols a and b are **independent**
- The set Σ^* of strings on alphabet Σ is a monoid w.r.t. the operation $\cdot$ of concatenation
- The trace monoid M(D) is the quotient monoid $\Sigma^*_D / \equiv_D$.
- Given a string w, $[w]_D$ is the trace represented by string w
- A dependency graph G(D) ia graphical representations of dependency relation D. G(D) is isomorphic to M(D).

Histories

- Given n processes, each with its own alphabet Σ_i
- An elementary history $\pi(a)$ is an n-tuple consisting of one-symbol strings a in positions where $a \in \Sigma_i$, the empty string ε elsewhere
- A history is a concatenation of elementary histories
- The monoid of histories $H(\Sigma_1, \Sigma_2, \ldots, \Sigma_n)$ is isomorphic with the monoid of traces over dependency $\Sigma_1^2 \cup \Sigma_2^2 \cup \ldots \cup \Sigma_n^2$.
- An ordering of events may be established given a history

Trace Languages

- Trace language over D: any set of traces over D
- Trace projection of trace t onto dependency C: $\pi_C(t)$
- The synchronization of string language L_1 over Σ_1 with the string language L_2 over Σ_2 is defined as $(L_1 \parallel L_2)$ over $(\Sigma_1 \parallel \Sigma_2)$, such that $w \in (L_1 \parallel L_2)$ iff $\pi_{\Sigma 1}(w) \in L_1$ and $\pi_{\Sigma 2}(w) \in L_2$.

TLA+ Logic

- Temporal Logic of Actions, developed by Leslie Lamport
- TLA+ combines temporal logic with a logic of actions
- TLA+ formulas describe the behavior of a system
- Temporal aspect: primed and non-primed variables:
  - Non primed, x, means “the current value of x”
  - Primed, x', means “the value of x at the next step”
- Action: a Boolean formula containing constants, variables, and primed variables
- State function: an expression containing constants and non-primed variables only
- Action A is enabled in state s iff there exists a state t such that (old-state s, new state t) satisfies A

TLA Syntax

- P: satisfied iff true for the initial state
- $[A]_f$: satisfied iff every step satisfies A or leaves f unchanged
- $\Box F$: satisfied if F is always true
- $WF_f(A)$: weak fairness of A: if $A \wedge (f' \neq f)$ ever becomes enabled and remains enabled forever, then infinitely many $A \wedge (f' \neq f)$ steps occur
- $SF_f(A)$: strong fairness of A: if $A \wedge (f' \neq f)$ is enabled infinitely often, then infinitely many $A \wedge (f' \neq f)$ steps occur
- $F \rightarrow^{+} G$: G is true for at least as long as F is
- $\Diamond F$: F is eventually true, equivalent to $\neg\Box\neg F$
- $F \sim G$: F leads to G: whenever F, eventually G: $\Box(F \Rightarrow \Diamond G)$

Process Calculi

- A process calculus or process algebra is a tool for the formal modeling of a concurrent system
- A process calculus comprises
  - tools for the high-level description of interactions, communications, and synchronizations between processes
  - algebraic laws that allow to manipulate descriptions and prove equivalences between processes
- Three very influential process calculi:
  - Calculus of Communicating Systems (CCS)
  - Communicating Sequential Processes (CSP)
  - π-Calculus

Calculus of Communicating Systems

- Introduced by Robin Milner around 1980
- Syntax: $P ::= \emptyset \mid a.P_1 \mid A \mid P_1 + P_2 \mid P_1|P_2 \mid P_1[b/a] \mid P_1\backslash a$
- $\emptyset$ is the empty process
- Process a.P can perform action a and continue as P
- A = P defines identifier A that refers to process P
- $P_1 + P_2$ is the non-deterministic choice between and P_1 and P_2
- $P_1|P_2$ means the two processes are executed concurrently
- P[b/a] is process P with all actions a replaced by b
- P\a is process P without action a

Communicating Sequential Processes

- Introduced by Sir C. A. R Hoare in 1978
- Originally designed as a concurrent programming language
- Then refined into an algebraic theory
- Used for specification and verification of concurrent systems
- Has enjoyed some success in industrial applications
- Focus on dependable and safety-critical systems
- CSP describes systems in terms of component processes that
  - Operate independently
  - Interact through message passing
- Processes may be defined both as sequential processes or as the parallel composition of more primitive processes

CSP Primitives

- Events: communications or interactions:
  - Atomic names (e.g., on, off)
  - Compound names (e.g., valve.open, valve.close)
  - Input events, ? = “reads” (e.g., mouse?xy)
  - Output events, ! = “writes” (e.g., terminal!message)
- Primitive processes, representing fundamental behaviors
  - STOP, the deadlock process
  - SKIP, successful termination

CSP Algebraic Operators

- a → P [prefix] Wait for event a, then proceed as P
- (a → P)□(b → Q) [deterministic choice]
  - if event a then P, else, if event b then Q
- (a → P)⊓(b → Q) [nondeterministic choice]
  - either a → P or b → Q
- P ||| Q [interleaving] P and Q in parallel with interleaving
- P|[X]|Q [interface parallel]
  - P and Q can proceed only after they both accept the same event in X
- P\X [hiding]
  - execute P after removing any occurrence of the events in X

CSP Syntax

- Proc ::= STOP | SKIP

| e → Proc	(prefixing)
| Proc ☐ Proc	(external choice)
| Proc ⊓ Proc	(nondeterministic choice)
| Proc ||| Proc	(interleaving)
| Proc |[X]| Proc	(interface parallel)
| Proc \ X	(hiding)
| Proc ; Proc	(sequential composition)
| if b then Proc else Proc	(Boolean conditional)
| Proc ▹ Proc	(timeout)
| Proc △ Proc	(interrupt)

Semantics

- The CSP syntax may be given several different formal semantics
- Operational Semantics: meaning given in terms of operations
- Algebraic semantics
- Denotational semantics
  - Traces model, based on trace theory
  - Stable failures model
  - Failures/divergence model

π-Calculus

- May be regarded as a continuation of CCS
- Parallel counterpart of λ-calculus
- The syntax of π-calculus allows one to represent
  - parallel composition of processes,
  - synchronous communication between processes through channels,
  - creation of new channels,
  - replication of processes
  - nondeterminism.
- Process: an abstraction of an independent thread of control
- Channel: an abstraction of a communication link b/w processes

Syntax of π-Calculus

Let P and Q denote processes. Then

- P | Q denotes a process composed of P and Q running in parallel
- a(x).P denotes a process that waits to read a value x from the channel a and then, having received it, behaves like P
- $\overline{a}$<x>.P denotes a process that first waits to send the value x along the channel a and then, after x has been accepted by some input process, behaves like P
- (va)P ensures that a is a new channel in P
- !P denotes an infinite number of copies of P, all running in parallel.
- P + Q denotes a process that behaves like either P or Q
- 0 denotes the inert process that does nothing

π-Calculus Example

Client-server communication:

$$!incr(a, x).\overline{a}\langle x+1\rangle \mid (\nu\ res)(\overline{incr}\langle res, 17\rangle \mid res(y))$$

Infinite copies of a server accept messages on a channel called “incr” containing a channel name a and a number x, then send on channel a the result of computing x + 1.

In parallel, a client creates a new channel called “res” and sends a message containing channel name “res” and 17 to the channel called “incr”; at the same time, it accepts messages containing the result, y, on channel “res”

Congruence

Structural congruence is the least equivalence relation preserved by the process constructs and satisfying:

- $P \equiv Q$, if Q can be obtained from P by renaming bound names
- $P \mid Q \equiv Q \mid P$
- $P + Q \equiv Q + P$
- $(P \mid Q) \mid R \equiv P \mid (Q \mid R)$
- $P \mid 0 \equiv P$
- $(\nu x)(\nu y)P \equiv (\nu y)(\nu x)P$
- $(\nu x)0 \equiv 0$
- $!P \equiv P \mid !P$
- $(\nu x)(P \mid Q) \equiv (\nu x)P \mid Q$, if x is not a free name in Q

Reduction Semantics

Reduction relation: $P \rightarrow P'$ means P can become P' after performing a computation step.

$\rightarrow$ is defined as the least relation closed under the rules:

- $\overline{a}\langle x\rangle.P \mid a(y).Q \rightarrow P \mid Q[x/y]$
- If $P \rightarrow Q$, then also $P \mid R \rightarrow Q \mid R$
- If $P \rightarrow P'$ and $Q \rightarrow Q'$, then also $P + Q \rightarrow P'$ and $P + Q \rightarrow Q'$
- If $P \rightarrow Q$, then also $(\nu x)P \rightarrow (\nu x)Q$
- If $P \equiv P'$ and $P' \rightarrow Q'$ and $Q' \equiv Q$, then $P \rightarrow Q$

Thank you for your attention