Applied Concurrency Theory
Lecture 1 : Introduction

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About us

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What is concurrency?

What is concurrency?

- A branch of computer science
- Several actors (or subsystems, machines, computers, processors, components, processes, threads…)
  - Each actor behaves individually
  - A common task to accomplish by all actors
  - (often:) Shared resources between actors
  - Co-operation between actors (accomplish the common task)
  - Competition between actors (access the shared resources)
- Specific problems
- Corpus of mathematical results (‘Concurrency theory’)

Concurrency is everywhere

- In computer hardware:
  - in processors, fast memories, buses, embedded devices, etc.
  - from the lowest levels (gates, netlists)
  - to the highest levels (supercomputers)

- In computer software:
  - multi-user, multi-task operating systems
  - parallel programming (threads, processes)

- In networking and distributed systems:
  - computer networks, Internet, GSM
  - aerospace, trains, power grids, etc.

Concurrency is difficult

- Faster but more difficult than sequential computing

- Frequent errors
  - Deadlocks
  - Race conditions
  - Loss of global consistency

- Additional reasons for complexity
  - Communication may fail (e.g., unreliable network)
  - Some actors may fail (e.g., node crash)

Strategies to handle concurrency

- 1. Don’t use it
  Avoid concurrency as much as possible

- 2. Only use ‘easiest’ forms of concurrency
  - Pipelining (actors organized along a simple flow of data)
  - Synchronous computing (actors scheduled by a central clock)

- 3. When concurrency is absolutely needed:
  Learn how to master it

A brief history of concurrency

Overview

- Concurrency in computing: since the 60s
  - hardware design
  - software and system design

- Before: concurrency studied in other contexts
  - coordination of humans acting together (work, dance, music)
  - coordination of machines (e.g., trains)

- In computing, concurrency has no linear history
  - no continuous progress
  - past knowledge is often forgotten
  - major scientific/technical regressions

Concurrency in hardware design (1/3)

- Initially, asynchronous logics
  - the first hardware designs were asynchronous (in the 60s)
  - but too difficult at that time
- Then, advent of synchronous logics
  - all parts of the circuit scheduled by a clock
  - a proper methodology for designing reliable complex circuits
  - today: most ASICs and CAD tools are synchronous
- Today, synchronous logics faces limitations
  - problems scaling up to high frequencies and complex VLSI
  - energy (clocks waste energy), secrecy (EM radiations)
- Asychronous logics is back!

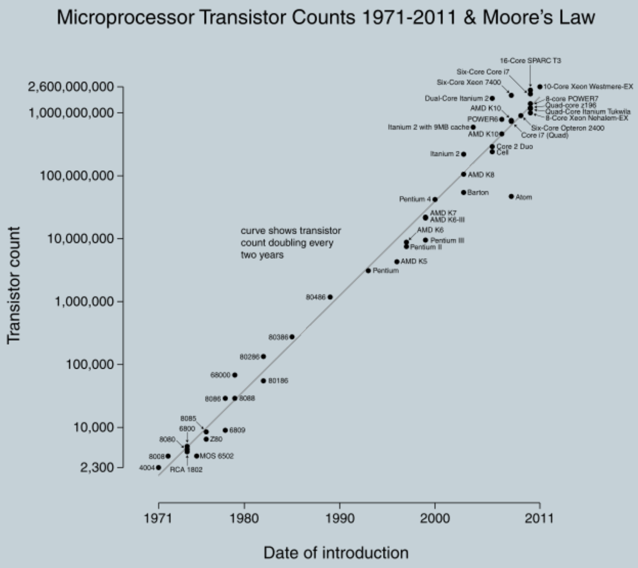
Concurrency in hardware design (2/3)

- In the first computers, a single CPU did everything
- Then, advent of multiprocessing (60s and 70s)
  - asymmetric: dedicated processors (I/O, arithmetic, graphics, crypto)
  - symmetric: multiple identical CPUs
  - shared memories, caches
  - parallel computing
- Progressive merge with telecommunications/networking
  - client/server applications
  - distributed systems
  - networks of workstations (NoW)
  - clusters, grids
  - Web services
  - supercomputing, high-performance computing

Concurrency in hardware design (3/3)

Lot of concurrency inside CPUs:

- Pipelining
- Multi-level caching
- Branch prediction



Moore law coming to an end:

- Clock frequency cannot increase any more
- Sequential processors reached performance peak
- Next step: multi-core (‘many-core’) processors

Concurrency in software design (1/3)

- Goal: How to program parallel computers?
- Low-level (hardware-oriented) approaches
  - shared memory / shared variables
  - study of problems: e.g., race conditions, deadlocks
- Higher-level (language-oriented) approaches
  - Petri nets (1962)
  - Simula (1967): multiple actors and coroutines
  - Algol 68 (1968): begin A , B end
  - PL/1 (1973): multitasking
  - Unix Bourne shell (1977): operators & (concurrent) and | (pipeline)
  - (concurrency much less easier in today's mainstream languages!)

Concurrency in software design (2/3)

- In the 70s
  - deep studies to understand concurrency issues
  - new language features for safer concurrent programming (semaphores, critical sections, monitors, rendezvous, etc.)
- In the 80s
  - Pascal and C take off: no support for concurrency
  - yet, Ada and Erlang have built-in concurrency
  - automated verification techniques for concurrent problems (protocol engineering, state exploration, model checking)
  - theoretical advances (process calculi, process algebra)

Concurrency in software design (3/3)

- In the 90s
  - C++: no support at all for concurrency
  - Java: a major regression to low-level programming
    ignores all lessons in designing better concurrent languages
    strong criticisms: Per Brinch Hansen, William Pugh
  - UML: an imprecise model of concurrency
  - silent progress in parallel compilers
- In the 2000s

  significant progress in analyzing concurrent systems with:
  - probabilistic behaviours
  - (hard or soft) real-time aspects

Concurrency today

Concurrent machines at hand

- For long, concurrent machines were rare:
  - Reserved to big military or civil projects
  - Sometimes available in research labs

- Now, they are available to the masses:
  - Your laptop is probably dual-core or quad-core
  - Machines with 24 cores already exist
  - Clusters and grids accessible from the desktop

- Concurrency is now a major concern in industry

Impact on software (1/2)

- Most existing software
  - was designed for sequential machines (e.g., Wintel)
  - is not ready for concurrency

- Major revisions will be needed for:
  - exploiting multi-core machines
  - exploiting cloud computing resources
  - developing reliable concurrent systems and programs

Impact on software (2/2)

- Mainstream programming languages are not ready:
  - C and C++: nothing for concurrency
  - Java: a catastrophe
  - Ada and Erlang: barely used
- New software must be developed to help designing and verifying
  - asynchronous circuits / architectures
  - concurrent software programs

Goals of the block course

Three goals

- Get acquainted with concurrency
  - Recognize concurrent problems where they are
  - Learn vocabulary and key concepts

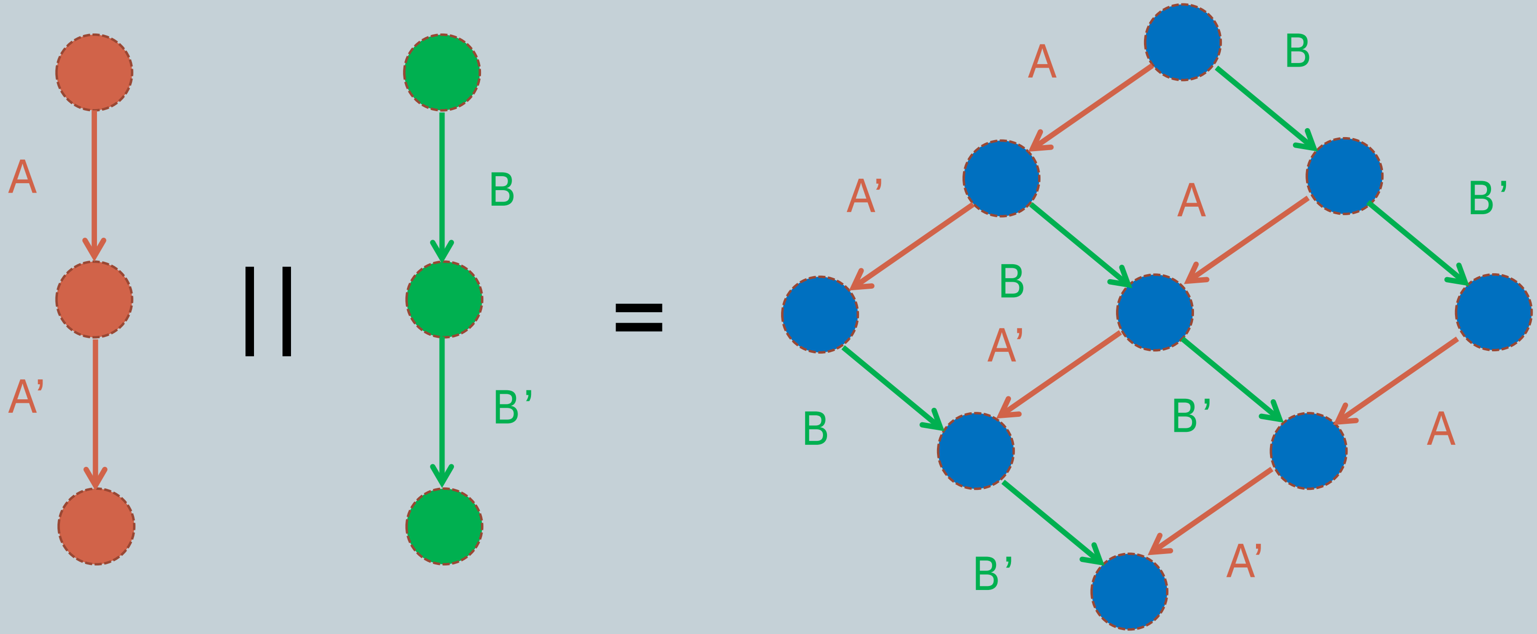
- Learn various languages for concurrency
  - Process calculi
  - Automata-based languages
  - Semantic concepts: SOS, LTS, etc.

- Experiment with state-of-the-art tools
  - a ‘Matlab reflex’ for concurrency
  - Tools from Grenoble, Oxford, and Saarland

Key concepts of concurrency

Interleaving

- Several actors have to execute actions independently
- A global observer sees ‘diamonds’ of actions



State explosion – combinatorial explosion

- A consequence of interleaving

- The number of states is exponential in the number of concurrent actors:
  - two actors: planary diamonds
  - three actors: cubes
  - N actors: hypercube with N dimensions

- State explosion is a major problem for verification techniques based on exhaustive state explorations

Processes vs Threads

Two main approaches to communication between actors

  - shared memory (e.g., blackboards)
  - message passing (e.g. e-mail)

- Shared memory → actors are called ‘threads’
  - Close to hardware and usually efficient
  - Multiple incompatible semantics (Posix, etc.)
  - Often dependent on hardware ⇒ portability problems
  - Low-level ⇒ makes proofs and automated reasoning difficult

- Message passing → actors are called ‘processes’
  - Higher abstraction level, more suitable for formal analysis
  - Can model hardware, software, and networking problems
  - Perhaps less efficient to implement (?)

Nondeterminism

- A concept borrowed from particle physics
- The future evolution of a concurrent program cannot be predicted, even if one fully knows its past history and its current state
  - Each actor evolves at its own speed
  - Some algorithms are intrinsically nondeterministic
- A major difference wrt sequential programming
- Nondeterminism makes life much harder:
  - each state may have several possible futures
  - execution runs / tests are not reproducible

Race conditions

- Nondeterministic behaviour arising from threads accessing a common resource (shared variable)

- Example: 2 threads and 1 shared variable X

  Initially: X = 0

  - thread 1: X := X + 1
  - thread 2: if X = 0 then X := 2 * X + 1
    (hypothesis: testing X and assiging X are two different steps)

  Finally: X = 1, 2, or 3 depending on relative execution speeds

- Race condition also exists with electronic signals

Critical sections

- Approaches proposed to avoid race conditions:
  - while an actor is accessing shared resources, block other actors
  - other actors have to wait until the first actor has finished

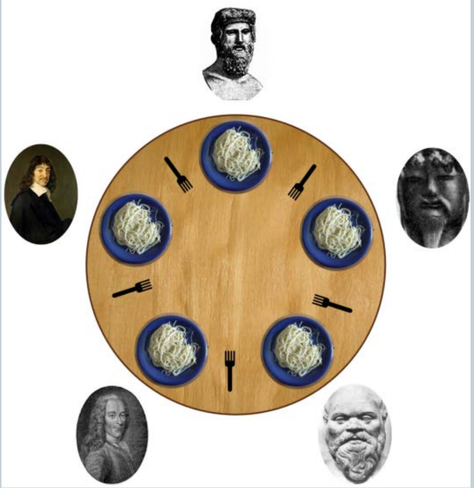
- Test-and-set instructions
  - simplest form, implemented as microprocessor instructions
    example: if X = 0 then X := 1 (single, atomic instruction)

- Locks
  - one thread becomes 'owner' for a limited time (aquire/release)
  - examples: semaphores, object locks in Java

- Critical sections
  - piece of code to be executed atomically
    example: critical_begin if X = 0 then X := 2 * X + 1 critical_end
  - examples: monitors, conditional critical sections, etc.

Deadlocks

- Improper use of critical sections / locks / etc.
- Each actor is waiting to access shared resources blocked by other
- Example: the dining philosophers problem
  - rule: each philosopher needs two forks
  - if each philosophers starts by taking the left fork, then everyone is blocked
  - various solutions exist (see Wikipedia)



Local deadlocks and livelocks

- A deadlock is a global problem: everyone is blocked
  - there are similar related issues

- Local deadlocks:
  - starvation: one or several actors are blocked
  - coalitions: certain actors join forces to prevent others from accessing shared resources

- Livelocks:
  - similar to deadlocks, except that actors are not blocked but are constantly active without being productive

Rendezvous

- High-level alternative to shared variables and locks
- Principle:
  - two (or more) actors decide to meet at a given point RV
  - the first actor arrived at RV waits for the others (and so on)
  - when all actors are ready, they can exchange data
  - after the rendezvous, each actor restarts independently
- Combines in a single mechanism
  - Synchronization between actors
  - Communication by messages
- Clean semantics preserving modularity

Message queues

- Rendezvous is ‘synchronous’:
  - all actors have to be there simultaneously
  - not to be confused with synchronous computing (clocks)
- Alternative approach:
  - an actor S sends a message M to another actor R
  - M is put in a message queue (e.g., FIFO queue)
  - S is not blocked and continues its execution after sending M
  - some time later, R checks the queue and reads M
- Popular model, but theoretical problems
  - queue is finite: overflow issues (M discarded or S blocked)
  - queue is infinite: S can continuously fill in the queue

Structure of the block course

Six lectures

September

- 1. Introduction
- 2. Process calculi (LOTOS)
- 3. Next-generation formal methods (LOTOS NT)
- 4. Pi-calculus and mobility

October

- 5. Probabilistic systems (PRISM)
- 6. Stochastic and timed systems (MODEST)

Four projects (lab exercises)

September:

- Project #1. LOTOS and LOTOS NT
- Project #2. PIC (pi-calculus)

deadline is October 1st (12:00)

October:

- Project #3. PRISM
- Project #4. MODEST

deadline is October 12 (12:00)

Some challenges

- Challenges are small exercises (< 1 hour) to be done after each lecture before the next one

- ‘Without such exercises, your students will attend the lectures and wait until the end of September to undertake their projects; suddenly, they will realize that they have to produce something, that they are late, and they will start panicking.’

  (a respected German professor)

Today's challenge

Starting up

- Get from the CMS the document entitled: *How to install the software tools needed for the course*?

- The 'official' solution is strongly advised
  - Install Virtual Box 4.1.22 on your machine
  - Install the AppliedConcurrencyTheory virtual machine
  - Request your CADP license to register your software

- Test if the tools are properly installed:
  - Type the shell command: **`bcg_edit $CADP/demos/demo_13/A1.bcg`**
  - Save the drawing as a PostScript file
  - Email this file to Alexander (agrafbrill@depend.cs.uni-saarland.de)

References

A few references

- Wikipedia:
  - Usually informative and well-done
  - Read more about the terms mentioned in this lecture: asynchronous circuit, nondeterminism, semaphore, deadlock, etc.

- Critical assessment of concurrency in C/C++
  - Hans-J. Boehm. *Threads Cannot Be Implemented As a Library.* PLDI 2005. http://www.hpl.hp.com/techreports/2004/HPL-2004-209.pdf

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  - Per Brinch-Hansen. *Java's insecure parallelism*. 1999. http://brinch-hansen.net/papers/1999b.pdf
  - J. Manson , W. Pugh, S. V. Adve. *The Java memory model*. POPL 2005 http://www.cs.umd.edu/~pugh/java/memoryModel/