CS 3211 – Parallel & Concurrent Programming Introduction

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http://www.comp.nus.edu.sg/~abhik/CS3211/index.html
Also see IVLE Lesson Plan (updated every week)

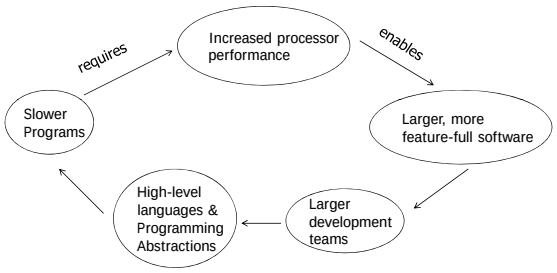
Sequential Programming

- Single thread of control flow.
- One program counter.
  - Advances by executing an instruction.
- Standard programming languages
  - C, Java.
  - Sequential Java program may have many passive objects
    - Only one active flow of control.

Why Concurrent Programming?

- Wide rise of multi-cores
  - Machines with 4 or more cores are common.
  - Intel already has a research processor with 80 cores !!
  - Why so ?
    - Processor speeds have enabled more complex programming languages and tasks.
    - But, is this not self-sustaining?

The cycle [Larus, MSR-TR 08]



Free lunch must end!

`` For the past three decades, improvements in semiconductor fabrication and processor implementation produced steady increases in the speed at which computers executed existing sequential programs. The architectural changes in multicore processors benefit only concurrent applications and therefore have little value for most existing mainstream software. For the foreseeable future, today's desktop applications will not run much faster than they do now. In fact, they may run slightly slower on newer chips, as individual cores become simpler and run at lower clock speeds to reduce power consumption on dense multicore processors ….

Free lunch must end!

… That brings us to a fundamental turning point in software development, at least for mainstream software. Computers will continue to become more and more capable, but programs can no longer simply ride the hardware wave of increasing performance unless they are highly concurrent. Although multicore performance is the forcing function, we have other reasons to want concurrency: notably, to improve responsiveness by performing work asynchronously instead of synchronously. For example, today's applications must move work off the GUI thread so it can redraw the screen while a computation runs in the background."

- *from "Software and the Concurrency Revolution", ACM Queue 05.*

On concurrency

- Being integrated into mainstream languages
  - Java, C#
- Harder to program and understand
  - Many inter-leavings even when each thread has one path.
  - Cyclic debugging not possible – cannot reproduce an observable error !

Thread 1	Thread 2
X = 1; // should be 0	X = 2; Y = X; printf("%d", y);

Possible runs

- X = 1;
- X = 2;
- Y = X;
- Print Y Error not exhibited.

- X = 2;
- X= 1;
- Y = X;
- Print Y Error is exhibited.

In this course

- Concurrent Programming (primarily)
  - Principles, rather than tricks
    - Sometimes high-level modeling languages used to convey principles.
    - Java is used to illustrate concrete issues.
- Parallel Programming (approx 3-4 lectures)
  - Material will be given.
- Textbook (closely followed for Concurrent Programming, but no coverage of parallel programming)
  - *Concurrency: State Models & Java Programs* by Jeff Magee and Jeff Kramer
    - Publisher: Wiley
    - ISBN 0-471-98710-7

Topics (1)

- Concurrency as a concept
  - Threads/Processes
  - Interleaving among threads
  - Communication mechanisms among threads
    - Shared Objects
    - Message Passing
- A glimpse of these concepts today

Topics (2)

- Thread Communication in details
  - Shared obj. & Mutual exclusion
  - Monitors
  - Properties to preserve
    - No deadlock, Safety, Liveness
  - Dynamic Thread Creation
- Multi-threaded Java will be used in these assignments.

Topics (3)

- Parallel Programming
  - Libraries to extend a sequential programming language
  - Message Passing Interface (MPI) on top of C
- Parallel programming constitutes about 1/3 of course.
  - **Assignment will have to involve C programming.**
  - **No tutorial on C programming will be given.**
    - You are expected to learn it on your own.
- Course outline in course webpage
  - http://www.comp.nus.edu.sg/~abhik/CS3211/index.html

Assessment

- Mark distribution
  - Midterm: 20% [on the 7th week, in class, 4th March 2010]
  - Programming Assignments: 30%
    - Concurrent Programming: 4 assignments, 5 marks each = 20 marks
    - Parallel Programming: 1 bigger assignment, 10 marks = 10 marks
  - Final : 50%
- Pre-requisites: CS2106
- IVLE Lesson Plan will be updated every week

The people

- My e-mail: abhik@comp.nus.edu.sg, Off: COM1 #03-20
- Your TA [responsible for tutorials]
  - Qi Dawei dawei@comp.nus.edu.sg
  - Seth Normand Hetu seth.hetu@gmail.com
- Guest lecture on multi-threaded Java programming
  - Ju Lei julei@comp.nus.edu.sg
- Queries, and help with assignments
  - Post your queries to the IVLE Discussion forum, please.
  - Email Ju Lei julei@comp.nus.edu.sg and
  - me abhik@comp.nus.edu.sg
  - You can also ask your queries to the TAs during tutorials.

A Concurrent Modeling Language

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Reading for this portion appears in E-reserves, see Lesson Plan.

We now discuss …

- SPIN --- a tool for modeling complex concurrent and distributed systems.
- Provides:
  - Promela, a protocol meta language
  - A checker
  - A random simulator for system simulation
- Why discuss it now?
  - To introduce the concepts in concurrency …
  - Without getting into full-scale multi-threaded Java programming at the very beginning.

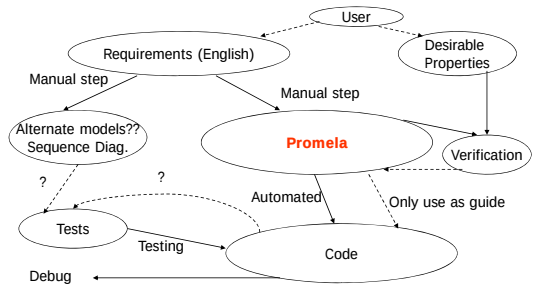
What is this modeling language?

- Describes concurrent systems
  - Depicts common concepts in concurrency
    - Threads / processes
    - Interleaving among threads/processes
    - Inter-process communication via shared variable updates
    - Inter-process communication via message passing
  - … and also other features such non-determinism within a process
    - Only in a modeling language.
- Yet, is higher-level than a programming language
  - Focus on concurrency concepts first, rather than details of Java

Our Usage

- Learn Promela, a modeling language.
  - Higher-level than a programming language.
- Use it to model simple concurrent system protocols and interactions.
- Gives a feel (at a small scale)
  - What are hard-to-find errors in concurrent programming?
  - Supported by a back-end checker which can show the errors to you as a UML Sequence Diagram!

Our primary usage



Why Promela ?

- Specification language to model *finite state* systems
  - Side remark: What is finite state?
- Models finite state concurrent processes which compute and communicate.
- Different flavors of concurrency & communication
  - Via global shared variables.
  - Via message channels
    - Synchronous communication (hand-shake)
    - Asynchronous communication (buffers)

Example 0

```
byte state = 0;

proctype A()
{ byte tmp;

    (state==0) -> tmp = state;
      tmp = tmp+1;
      state = tmp;
}

init { run A() ; }
```

state : Global Variable

tmp : Local Variable

(state==0) -> tmp = state is a guarded command (blocked if the guard is false).

Only one process created.

Final value of **state** is 1

Concepts in Example 0

```
byte state = 0;

proctype A()
{ byte tmp;

      (state==0) -> tmp = state;
        tmp = tmp+1;
        state = tmp;
}

init { run A() ; }
```

Plain sequential programming.

Use of guarded commands.

Only one active thread of control.

Looking inside a process

- Data Structures
  - Basic types : int, bool, bit, byte
  - Arrays
  - Structures (through typedef declarations)
- Just as in C/Java, not much going on here !
- Check SPIN manual for details
  - http://spinroot.com/spin/Man/Manual.html

Statements

- Assignments
- Boolean expressions
  - If true, then no-op else block
- Guarded commands
  - (state == 1) -> tmp = state;
  - Guard and body evaluated separately, be careful !!
  - If you want to evaluate them together
  - atomic { (state == 1) -> tmp = state; }
  - Effect of a test-and-set instruction

Example 1

```
byte state = 0;

proctype A()
{  byte tmp;

     (state==0) -> tmp = state;
     tmp = tmp+1; state = tmp;
}

init  { run A() ; run A();  }
```

What will happen here ?

We need to define how processes are scheduled to determine behaviors.

Process scheduling

- All processes execute concurrently
- Interleaving semantics
  - At each time step, only one of the "active" processes will execute (non-deterministic choice here)
  - A process is active, if it has been created, and its "next" statement is not blocked.
  - Each statement in each process executed atomically.
  - Within the chosen process, if several statements are enabled, one of them executed non-deterministically.
    - We have not seen such an example yet !

Example 1 - Revisited

```
byte state = 0;

proctype A()
{  byte tmp;

     (state==0) -> tmp = state;
     tmp = tmp+1; state = tmp;
}

init  { run A() ; run A();  }
```

Final val. of state can still be 1 ??

Problem of arbitrary shared variable access by several threads.

Concepts in Example 1

```
byte state = 0;

proctype A()
{  byte tmp;

     (state==0) -> tmp = state;
     tmp = tmp+1; state = tmp;
}

init  { run A() ; run A();  }
```

Several threads of control.

Interleaved execution among threads.

Shared variables for inter-thread communication.

Surprising results due to unforeseen interleavings !!

Example 2

```
bit  flag;
byte sem;
proctype myprocess(bit i)
{   (flag != 1) -> flag = 1;
    sem = sem + 1;
    sem = sem – 1;
    flag =  0;
}
proctype observer() {
     assert( sem != 2 );
}
```

```
init {
    atomic{
          run myprocess(0));
          run myprocess(1));
          run observer();
    }
}
```

All three processes Instantiated together

Concepts in Example 2

- Interleaved execution among threads.
- Shared variable communication
- Unintended shared variable values
  - Due to unforeseen interleavings
- And, a mechanism for
  - Specifying the unintended behavior
  - Producing the interleaving that produces this unintended behavior.
  - We only do this in our modeling environment – hard to do this for real programs!

Concepts in Example 2

- Initial values of sem, flag not given
  - All possible initial values are considered.
- The system being verified is the asynchronous composition
  - myprocess(0) || myprocess(1)
- The property is the invariant
  - always sem ≠ 2
- Local & global invariants can be specified inside code via assert statements.

More on assert

- Of the form assert B
  - B is a boolean expression
  - If B then no-op else abort (with error).
- Can be used inside a process (local invariants)
  - proctype P(…) { x = … ; assert(x != 2); ….}
- Or as a separate observer process (global invariants)
  - proctype observer(){ assert(x != 2);}
- Used to specify intended (and unintended) behaviors resulting from interleavings among threads.

Example 3

```
bit flags[2];
byte sem, turn;
proctype myprocess(bit id) {
   flags[id] = 1;
   turn = 1 – id;
   flags[1-id] == 0 || turn == id;
   sem++;
   sem--;
   flags[id] = 0;
}

init() {
   atomic{
      run myprocess(0);
      run myprocess(1);
      run observer(); }
   }
proctype observer() {
      assert( sem != 2 );
}
```


Issues

- Can you prove mutual exclusion ?
  - What purpose does turn serve ?
- Arrays have been used in this example.
  - Flags is global, but each element is updated by only one process in the protocol
  - Not enforced by the language features.
- Processes could alternatively be started as:
  - active proctype myprocess(…) {
  - Alternative to dynamic creation via run statement

So far …

- Process creation and interleaving.
- Process communication via shared variables.
- Standard data structures within a process.
- Assignment, Assert, Guards.
- NOW …
  - Guarded IF and DO statements
    - Within a process, if several statements are enabled, one of them executed non-deterministically!
  - Channel Communication between processes

Non-deterministic choice

- Choice of statements within a process
  - if
  - :: condition$_1$ -> … ; … ; …
  - …
  - :: condition$_k$ -> … ; … ; …
  - fi;
- If several conditions hold, select and execute any one (more behaviors for verification).
- If none hold, the statement blocks.

Loops

- Similar to the if-fi statement, we have a do-od statement.
- Repeat the choice selection forever.
  - Useful for modeling infinite loops pre-dominant in control software.
- Control can transfer out of the loop via a break statement in the flavor of the C language.

A loop which may terminate

```
byte count;

        proctype counter()
        {
                do
                :: count = count + 1
                :: count = count - 1
                :: (count == 0) -> break
                od;
        }
```

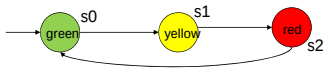
Enumerate the reasons for non-termination in this example

Concepts in previous example

- Non-determinism within a process
  - Not normal for threads in programs!!
  - A model is often, less detailed than a program.
- Possibility of programming non-terminating control software
  - See next example too.

A loop which will not terminate

```
active proctype TrafficLightController() {
    byte color = green;
    do
     :: (color == green) -> color = yellow;
     :: (color == yellow) -> color = red;
     :: (color == red) -> color = green;
     od;
}
```



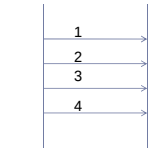
So far …

- Process creation and interleaving.
- Process communication via **shared variables**.
- Standard data structures within a process.
- Assignment, Assert, Guards.
- Guarded IF and DO statements
- NOW …
  - Channel Communication between processes

Channels

- Processes in our modeling language can communicate by exchanging messages across channels.
- Channels are typed.
- Any channel is a FIFO buffer.
- Handshakes supported when buffer is null.
- chan ch = [2] of bit;
  - A buffer of length 2, each element is a bit.
- Array of channels also possible.
  - Talking to different processes via dedicated channels.

Handshake or not?



Handshake communication
<!1, ?1>, <!2, ?2>, <!3, ?3>, ...
(only possible interleaving)
Buffer of length 2
!1, !2, ?1, !3, ?2, ...
(also possible)

What is the minimum sized buffer needed to allow this interleaving?

!1, !2, ?1, ?2, !3, !4, ?3, ?4, ...

Value-passing

```
chan ch =  [0] of bit;
active proctype sender()
{
     ch!1;
}
```

```
active proctype receiver()
{  bit  x;
    ch?x;
    printf("%d", x);
}
```

The value 1 is passed into local var. x via message passing.
In this example, the message passing was via a handshake
! is output, ? is input

Message retrieval

- ch ? X
  - Retrieve the earliest received (note: FIFO) message from the buffer for ch and store it into the local var. X on the receiver side.
- Receiving is always blocked if the corresponding channel buffer is empty.
- Similarly for sending.

An example with channels

```
chan name = [??] of byte;
proctype A() {
name!124;
name!121;
}

proctype B() {
     byte state;
     name?state
}
```

```
init { atomic { run A(); run B() } }
```

Enumerate the behaviors when:

?? is 0

?? is 1

?? is > 1

Another (more famous) example

```
#define p 0
#define v 1
chan sema = [0] of { bit };
proctype dijkstra_semaphore() {
byte count = 1;
do
:: (count == 1) -> sema!p; count = 0
:: (count == 0) -> sema?v; count = 1
od
}
```

```
proctype user()
{
 do
 :: sema?p;  /* critical section */
    sema!v; /* non-critical section */
od
}

init {
     run dijkstra_semaphore();
     run user(); run user(); run user()
}
```


Readings for today's lecture

- Basic SPIN manual
  - http://spinroot.com/spin/Man/Manual.html
  - Promela is the front end of the SPIN tool, a model checker. We will concern ourselves mostly about the modeling in cs3211.
- Chapter 3 of "The SPIN Model Checker" by Gerard J. Holzmann.
  - Scanned version made available from IVLE Lesson Plan (E-reserves).
- Lot of other material available online at
  - http://spinroot.com/spin/Man/index.html