Deterministic Concurrency

Candidacy Exam

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Motivation

Why Parallelism?

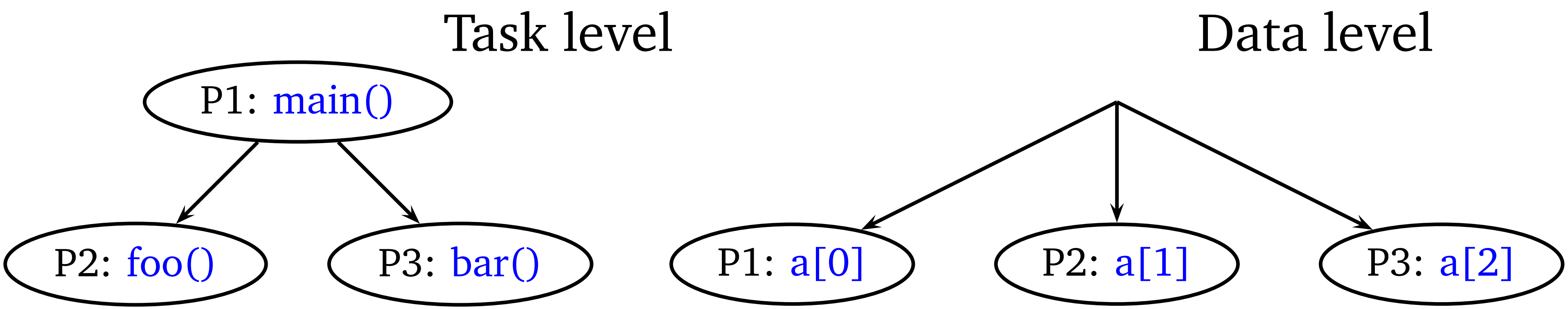
Past Vs. Future

- Power wall: Power vs. transistors
- Static vs Dynamic power
- Memory wall: Multiply vs. load and stores
- Faster sequential computer?
- Clock frequency

[Asanovic et al., The Landscape of Parallel Computing Research, 2006]

Programming Models

- Performance
- Psychological: Ease of use
- No. of processors
- Types of Parallelism



[Background and Jargon of Parallel Computing, Patterns for Parallel Programming, 2004]

Programming Models

Nested Data Level Parallelism

```
function quicksort(a) =
  if (#a < 2) then a
    else
      let pivot = a[#a/2];
        lesser = {e in a| e < pivot};
        equal = {e in a| e == pivot};
        greater = {e in a| e > pivot};
        result = {quicksort(v): v in [lesser,greater]};
  in result[0] ++ equal ++ result[1];

quicksort([8, 14, -8, -9, 5, -9, -3, 0, 17, 19]);
```

[Programming Parallel Algorithms, Blelloch, ACM Communications, 1996.]

The Data Race Problem

```
int x = 1;
bar() {
    x++;
}
foo() {
    spawn(bar);
    x++;
}
```

ld x

add x, x, 1

st x

The Data Race Problem

```
int x = 1;
bar() {
    x++;
}
foo() {
    spawn(bar);
    x++;
}
```

```
int x = 1;
bar() {
    lock(x);
     x++;
    unlock(x);
}
foo() {
    spawn(bar);
    lock(x);
     x++;
    unlock(x);
}
```

ld x

add x, x, 1

st x

High Level Data Races

T1

```
lock(m)
  x = x * 2;
  y = x + 2;
unlock(m)
```

T2

```
lock(m)
  read(x);
unlock(m)
..
lock(m)
  read(y);
unlock(m)
```

[Artho et al., High Level Data Races, 2003]

Non-determinism

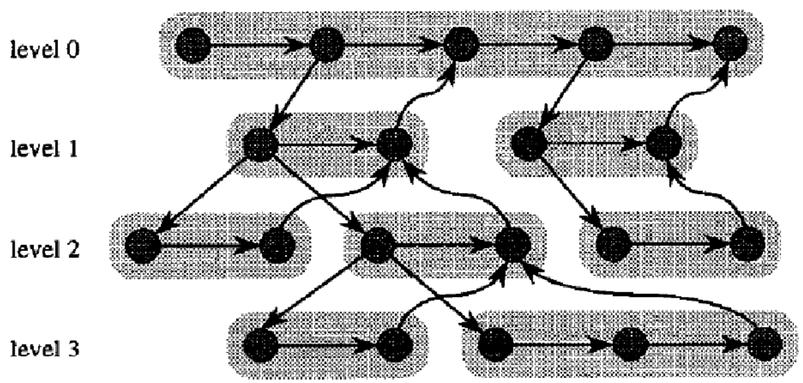
```
int x = 1;
void bar() {
        lock(m);
        x = x*2;
        unlock(m);
}
void foo() {
        spawn(bar);
        lock(m);
        x++;
        unlock(m);
        x = ?;
}
```

Output: 2, 3 or 4

x = 1	x = 1
bar: x = 1 * 2 = 2	foo: x = 2
foo: x = 3	bar: x = 2*2 = 4

Concurrent Programming Models

The Cilk Programming Model

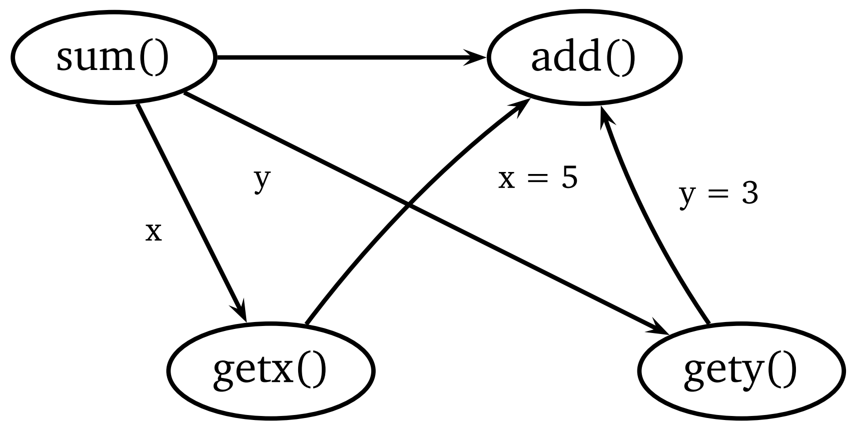


- Each thread is non-blocking
- Downward edges denote spawned threads
- Horizontal edges denote successors
- Work stealing scheduler
- Non-deterministic: Allows access to global resources

[Blumofe et al., Cilk: An Efficient Multithreaded Runtime System, 1995]

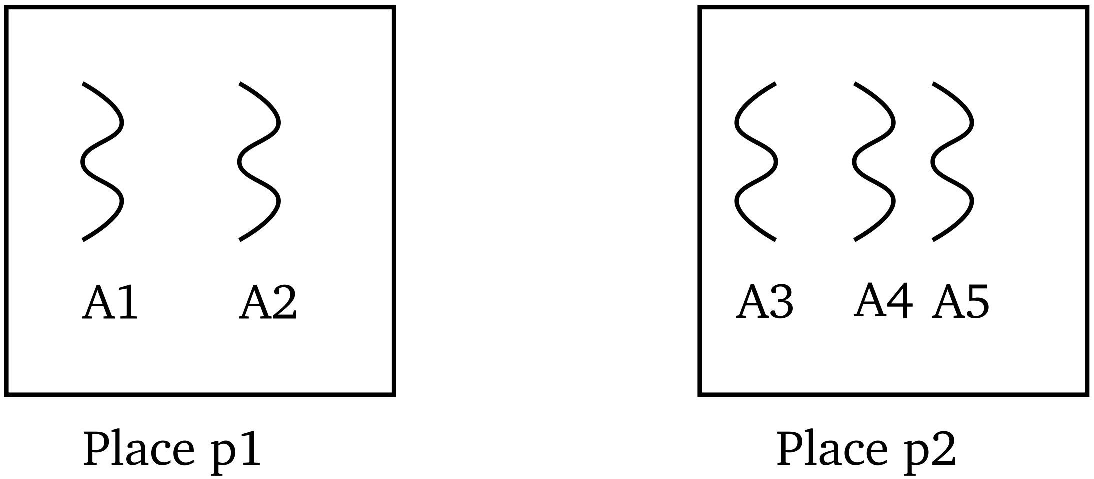
An Example in Cilk

```
thread sum() {
    cont int x, y;
    spawn_next add(?x, ?y);
    spawn getx (x);
    spawn gety (y);
}

thread getx (cont int x) {
   send argument (x, 5);
}

thread gety (cont int y) {
   send argument (y, 3);
}

thread add(int x, int y) {
   printf("%d", x + y);
}
```



The X10 Programming Language

- Concurrent programming model
- Activities are light weight threads
- Places represent distributed memory



[Charles et al., X10: An Object-Oriented Approach to Non-Uniform Cluster Computing, 2005]

The X10 Programming Language

- Activities created using *async*

```
async {
/* Body of async
executed locally */
}
```

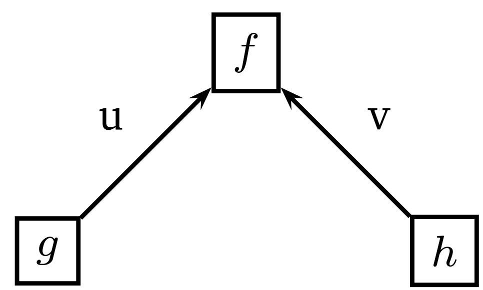
```
async (p2) {
/* Body of async
executed at p2 */
}
```

- Synchronization between activities through
  - *finish*
  - *atomic*
  - clocks
- Improper synchronization can lead to races

Deterministic Concurrent Programming Models

Kahn Networks

```
void f(int in u, int in v) {
    int i;
    bool b = true;
    while (1) {
      i = if (b) then wait (u) else wait (v);
      print (i);
      b = ~b;
    }
 }
```




```
void g(int out u) {
    u = 1;
    while (1) {
      send u;
    }
}
```

```
void h(int out v) {
    v = 0;
    while (1) {
      send v;
    }
 }
```

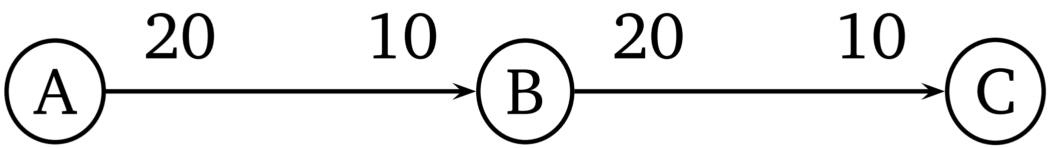
```
// Body of main program;
   f(u, v) par g(u) par h(v);
```

Properties of Kahn Networks

- **Wait**: Waits for the sender to send data
- **Send**: Nothing prevents a process to send
  - No two stations are allowed to send data on the same channel
- Behaves like FIFO queues
- Deterministic behavior

Problem: Unbounded Buffers

Synchronous Data Flow

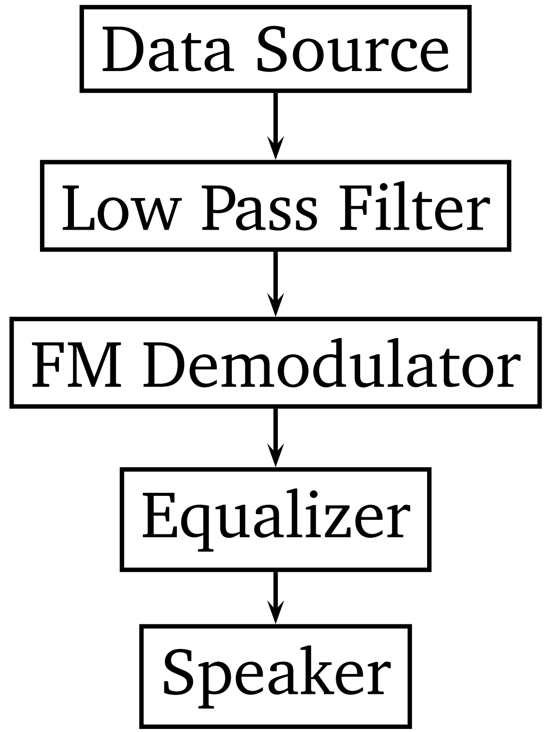


- Subset of Kahn Networks
- Actor: fires by removing tokens from its input edges and producing tokens on its output edges
- Edges represent communication channels, implemented as FIFO
- Each actor produces and consumes a fixed number (known apriori)
- Model suitable for DSP applications

The StreamIt Model

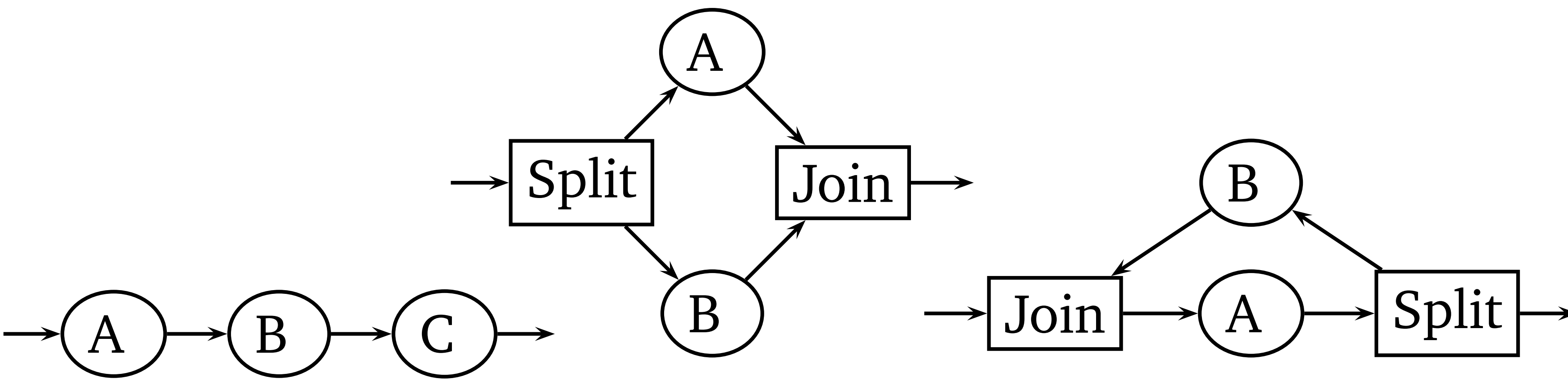
- A synchronous data flow language
- A structured model for streams

```
pipeline FMRadio {
    add DataSource();
    add LowPassFilter();
    add FMDemodulator();
    add Equalizer();
    add Speaker();
}
```



The StreamIt Model

- Filter
  - Autonomous unit of computation
  - No access to global resources
  - Communicates through FIFO channels: pop(), peek(index), push(value)



Esterel: A synchronous model

- Suited for reactive systems
- Follows the synchrony hypothesis
  Let t be the communication time
  - t arbitrary $\longrightarrow$ asynchrony
  - t predictable $\longrightarrow$ vibration
  - $\boldsymbol{t = 0}$ $\longrightarrow$ **synchrony**
- Notion of a global clock

[Berry et al., The ESTEREL Synchronous Programming Language, 1992]

An Example in Esterel

```
input COIN, TEA_BUTTON, COFFEE_BUTTON;
output SERVE_TEA, SERVE_COFFEE;
loop
        await COIN;
        await
            case TEA_BUTTON do emit SERVE_TEA;
            case COFFEE_BUTTON do emit SERVE_COFFEE;
        end await;
end loop;
```

Compiling Esterel

```
loop
emit A;
await C;
emit B;
pause
end
```

[Edwards, Tutorial: Compiling Concurrent Languages for Sequential Processors, TODAES, 2003]

Compiling Esterel

```
loop
emit A;
await C;
emit B;
pause
end
```

```
void tick() {
  static int s = 0;
  A = B = 0;
  switch (s) {
    case 0:
      A = 1;
      s = 1;
      break;
    case 1:
      if (C) {
        B = 1;
        s = 0;
      }
      break;
  }
}
```

```
main()
{
  for(;;)
    tick();
}
```

[Edwards, Tutorial: Compiling Concurrent Languages for Sequential Processors, TODAES, 2003]

Compiling Esterel

```
loop
emit A;
await C;
emit B;
pause
end
```

```
void tick() {
  static int s = 0;
  A = B = 0;
  switch (s) {
    case 0:
      A = 1;
      s = 1;
      break;
    case 1:
      if (C) {
        B = 1;
        s = 0;
      }
      break;
  }
}
```

```
main()
{
  for(;;)
    tick();
}
```

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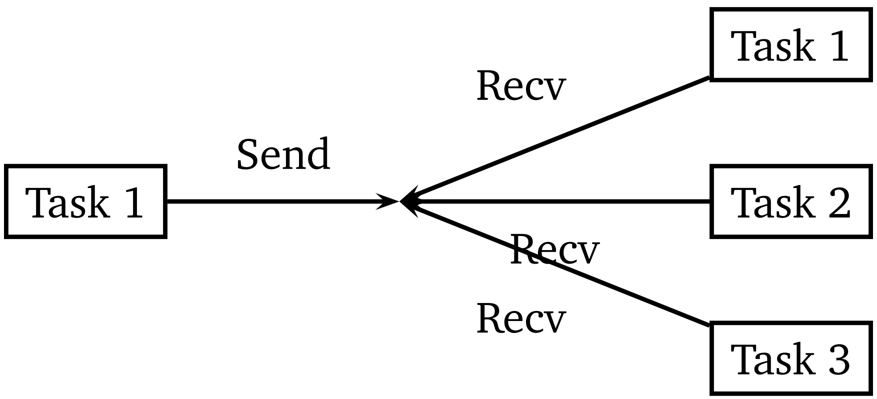
The SHIM Programming Language

The SHIM Model

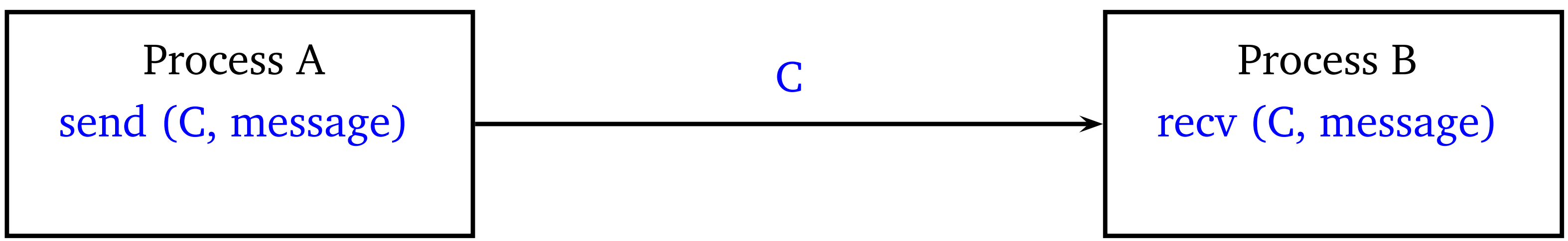
- Stands for *Software Hardware Integration Medium*
- Race free, scheduling independent, concurrent model
- Blocking CSP-style rendezvous communication



[Edwards et al., SHIM: A Deterministic Model for Embedded Systems, 2005.]

CSP

- Stands for Communicating Sequential Processes
- Model interactions between processes
- Supports synchronization, concurrency etc.
- Rendezvous, message passing



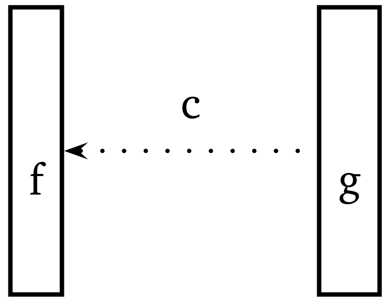
[[] Hoare, Communicating sequential processes. Commun. ACM 21, 8 (Aug. 1978), 666-677.]

SHIM = Kahn + CSP

An Example in SHIM

- Blocking: wait for all processes connected to *c*

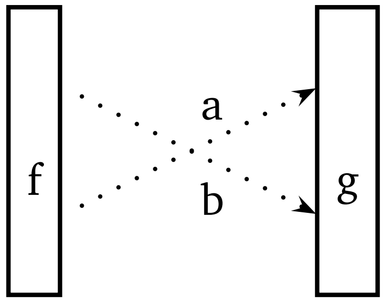
```
void f(chan int a) { // a is a copy of c
  a = 3; // change local copy
  recv a; // receive (wait for g)
  // a now 5
}
void g(chan int &b) { // b is an alias of c
   b = 5; // sets c
   send b; // send (wait for f)
  // b now 5
}
void main() {
  chan int c = 0;
  f(c); par g(c);
  c = c * 2;
}
```



[Tardieu et al., Scheduling-Independent Threads and Exceptions in SHIM]

The Problem

```
void main() {
 chan int a, b;
 {
    // Task 1
    a = 15, b = 10;
    send a;
    send b;
 } par {
    // Task 2
    int c;
    recv b;
    recv a;
    c = a + b;
  }
}
```



Analysis of Concurrent Programs

Why Analyze?

- Data Race Detection
- Deadlock Detection
- Optimization

Analysis of concurrent programs is generally harder than sequential programs

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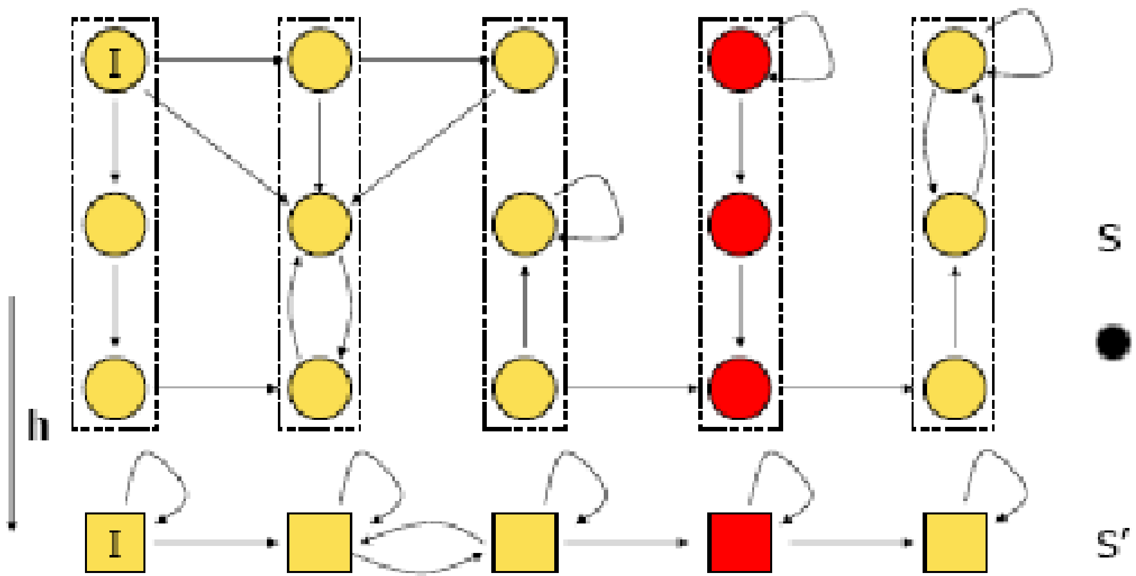
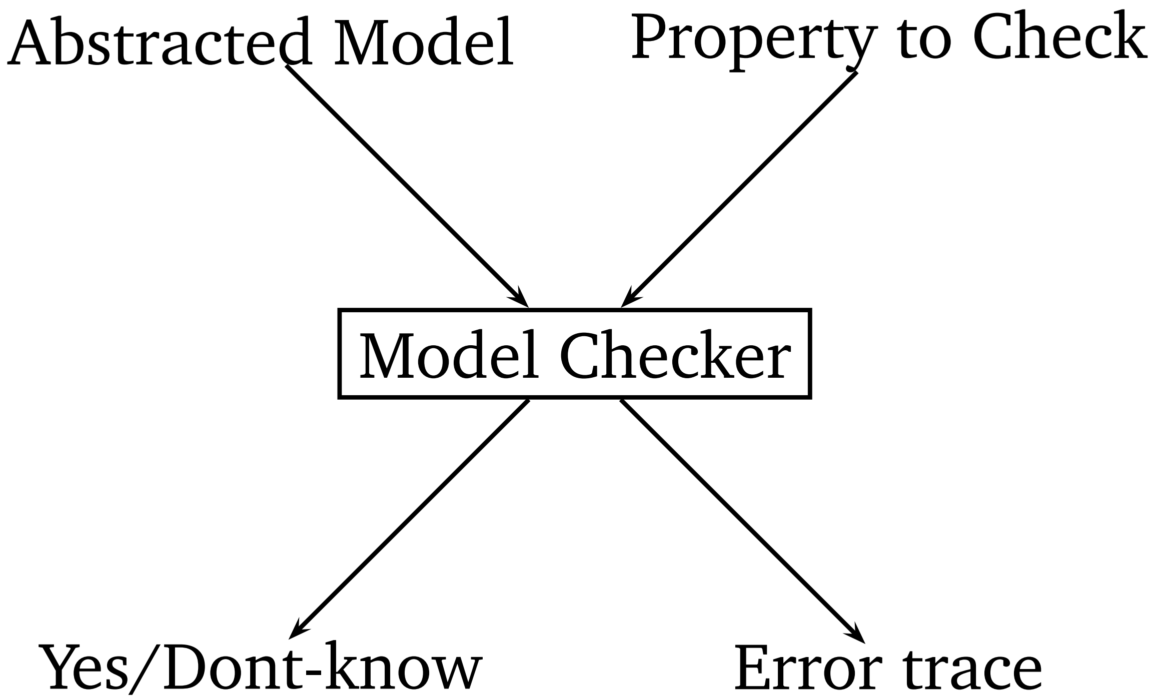
[Rinard, Analysis of Multi-threaded Programs, 2001.
Corbett, Evaluating Deadlock Detection Methods for Concurrent Software, 1996.]

Abstraction



[Clarke et al., Model checking and Abstraction, 1994]

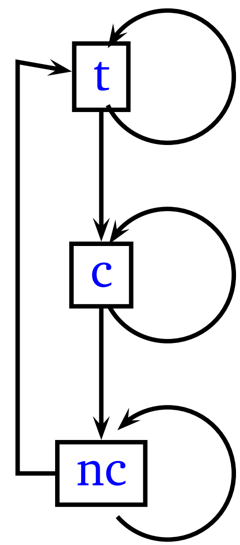
Model Checking



The SPIN Model Checker

```
mtype= {NONCRITICAL, TRYING, CRITICAL};
show mtype state[2];
proc type process(int id) {
  beginning:
    trying:
      state[id] = TRYING;
      if
        :: goto trying;
        :: true;
      fi;
    critical:
      state[id] = CRITICAL;
      if
        :: goto critical;
        :: true;
      fi;
    noncritical:
      state[id] = NONCRITICAL;
      if
        :: goto noncritical;
        :: true;
      fi;
    goto beginning;
}

init { run process(0); run process(1); }
```



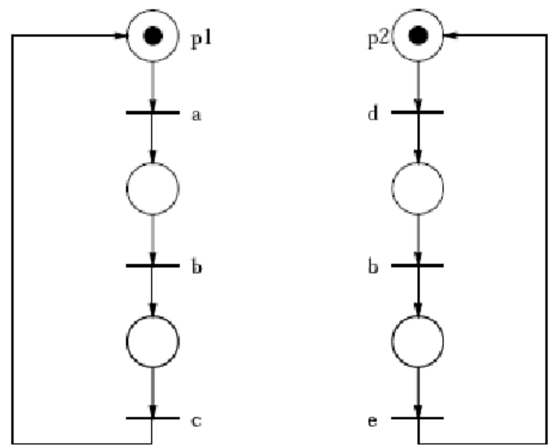

```
#define cs0 (state[0] == critical )
#define cs1 (state[1] == critical )
!(cs0 && cs1)
```

Using Petri Nets to analyze concurrent languages

- Reachability analysis (finding deadlocks etc.)
- To generate sequential code from concurrent programs

```
void ping() {
  for(;;) {
      send a;
      send b;
      send c;
  }
}
```

```
void pong() {
  for(;;) {
      send d;
      recv b;
      send e;
  }
}
```



[Lin, Efficient Compilation of Process-Based Concurrent Programs without Run-Time Scheduling, DATE 1998
Peterson, Petri Nets, ACM Computing Surveys 9, 1977.]

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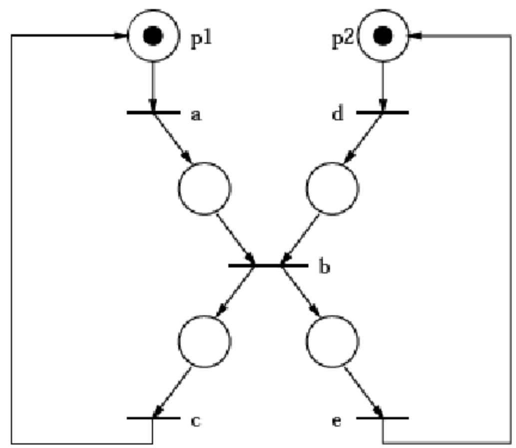

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Conclusions

- Problems with concurrent programming languages
  - Concurrent programs are generally harder to analyze
  - Bugs: Data Races, Deadlocks
- Future Work
  - A language that is race-free and deadlock-free
  - An auto-determinizing compiler