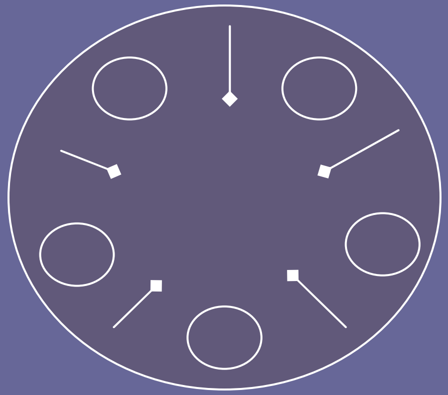
Model Checking and Testing

- Classical IPC Problem: Dining Philosophers
- Model Checking
  - Modeling Language: SMV
  - Specification Language: CTL
  - Presented by Jason Simas
- Testing
  - Implementation Language: Java
  - Presented by Evren Sahin

Dining Philosophers

- IPC Problem
  - Asynchronous processes & shared resources
    - Philosophers are processes
    - Resources are forks



- Solution: Modern Operating Systems pg. 127
  - Freedom from starvation/deadlock
  - Exclusive use of resources
  - Maximal usage of resources

Solution : Philosopher

```
#define N 5                   /*number of philosophers*/
#define LEFT  (i+N-1)%N       /*i's left neighbour*/
#define RIGHT (i+1)%N         /*i's right neighbour*/
#define THINKING 0            /*philosopher is thinking*/
#define HUNGRY   1            /*philosopher is trying to get the forks*/
#define EATING   2            /*philosopher is eating*/
typedef int semaphore;        /*semaphores are special kind of integers*/
int state[N];                 /*array to keep track of everyone's state*/
semaphore mutex;              /*mutual exclusion for critical regions (init 1)*/
semaphore s[N] ;              /*one semaphore per philosopher (init 0)*/
void philosopher(int i) {     /*i:philosopher number, from 0 to N-1*/
  while (TRUE) {              /*repeat forever*/
    think();                  /*philosopher is thinking*/
    take_forks(i);            /*acquire two forks or block*/
    eat();                    /*yum-yum, spaghetti*/
    put_forks(i);             /*put both forks back on table*/
  }
}
```

Solution : Other

```
void take_forks(int i) {   /*i:philosopher number, from 0 to N-1*/
  down(&mutex);            /*enter critical region*/
  state[i] = HUNGRY;       /*record fact that philosopher is hungry*/
  test(i);                 /*try to acquire 2 forks*/
  up(&mutex);              /*exit critical region*/
  down(&s[i]);             /*block if forks were not acquired*/
}
void put_forks(int i) {    /*i:philosopher number, from 0 to N-1*/
  down(&mutex);            /*enter critical region*/
  state[i] = THINKING;     /*philosopher has finished eating*/
  test (LEFT));            /*see if left neighbour can now eat*/
  test (RIGHT);            /*see if right neighbour can now eat*/
  up(&mutex);              /*exit critical region*/
}
void test (int i) {        /*i:philosopher number, from 0 to N-1*/
  if (state[i]==HUNGRY && state[LEFT]!=EATING && state[RIGHT]!=EATING) {
    state[i] = EATING;
    up(&s[i]);
  }
}
```

SMV : Overview

- Abstraction Level: pseudo instructions (137 loc)
- Model checked for 5, 4, and 3 philosophers
  - Checked both even and odd number of philosophers.
- Checked whether:
  - Each philosopher gets to eat infinitely often
    - No starvation, no deadlock
  - If a philosopher is eating, its neighbors are not eating
    - Exclusive use of resources
  - Possibility for non-neighbors to eat simultaneously
    - Maximal usage of resources

SMV : Model : Main : 5

```
MODULE main
VAR
  ph_0 : process philosopher (0, n, mutex, sems, states);
  ph_1 : process philosopher (1, n, mutex, sems, states);
  ph_2 : process philosopher (2, n, mutex, sems, states);
  ph_3 : process philosopher (3, n, mutex, sems, states);
  ph_4 : process philosopher (4, n, mutex, sems, states);
  mutex  : boolean;
  sems   : array 0 .. 4 of boolean;
  states : array 0 .. 4 of {THINKING, HUNGRY, EATING};
ASSIGN
  init (mutex) := 1;
DEFINE
  n := 5;
SPEC --ppl eat (no starvation)
  (AG ((AF ph_0.eating) & (AF ph_1.eating) &
       (AF ph_2.eating) & (AF ph_3.eating) & (AF ph_4.eating)))
SPEC --ppl eat with forks (mutual exclusion)
  (AG ((ph_0.eating -> (!ph_4.eating & !ph_1.eating)) &
       (ph_1.eating -> (!ph_0.eating & !ph_2.eating)) &
       (ph_2.eating -> (!ph_1.eating & !ph_3.eating)) &
       (ph_3.eating -> (!ph_2.eating & !ph_4.eating)) &
       (ph_4.eating -> (!ph_3.eating & !ph_0.eating))))
SPEC --ppl eat simultaneously
  (AG ((EF (ph_0.eating & ph_2.eating)) &
       (EF (ph_1.eating & ph_3.eating)) &
       (EF (ph_2.eating & ph_4.eating)) &
       (EF (ph_3.eating & ph_0.eating)) &
       (EF (ph_4.eating & ph_1.eating))))
```

SMV : Model : Main : 4

```
MODULE main
VAR
  ph_0 : process philosopher (0, n, mutex, sems, states);
  ph_1 : process philosopher (1, n, mutex, sems, states);
  ph_2 : process philosopher (2, n, mutex, sems, states);
  ph_3 : process philosopher (3, n, mutex, sems, states);
  mutex  : boolean;
  sems   : array 0 .. 3 of boolean;
  states : array 0 .. 3 of {THINKING, HUNGRY, EATING};
ASSIGN
  init (mutex) := 1;
DEFINE
  n := 4;
SPEC --ppl eat (no starvation)
  (AG ((AF ph_0.eating) & (AF ph_1.eating) & (AF ph_2.eating) & (AF
   ph_3.eating)))
SPEC --ppl eat with forks (mutual exclusion)
  (AG ((ph_0.eating -> (!ph_3.eating & !ph_1.eating)) &
       (ph_1.eating -> (!ph_0.eating & !ph_2.eating)) &
       (ph_2.eating -> (!ph_1.eating & !ph_3.eating)) &
       (ph_3.eating -> (!ph_2.eating & !ph_0.eating))))
SPEC --ppl eat simultaneously
  (AG ((EF (ph_0.eating & ph_2.eating)) &
       (EF (ph_1.eating & ph_3.eating))))
```

SMV : Model : Philosopher : Shell

```
MODULE philosopher (i, n, mutex, sems, states)
VAR
  insns : {thinking_, take_forks_, eating_, put_forks_};
  take_forks : {begin, down_mutex, state_hungry, if, state_eating,
    up_sem, up_mutex, down_sem, end};
  put_forks  : {begin, down_mutex, state_thinking, left_if,
    left_state_eating, left_up_sem, right_if,
    right_state_eating,right_up_sem, up_mutex, end};
ASSIGN
  ...
DEFINE
  left  := (i + n - 1) mod n;
  right := (i + 1)     mod n;
  leftleft   := (left + n - 1) mod n;
  leftright  := i;
  rightleft  := i;
  rightright := (right + 1) mod n;
  eating   := (insns = eating_);
  thinking := (insns = thinking_);
  hungry   := (insns = take_forks_);
FAIRNESS
  (AG (AF (running & mutex)))
```

SMV : Model : Philosopher : Main

```
next (mutex) := case
  take_forks = down_mutex & mutex : 0;
  take_forks = up_mutex : 1;
  put_forks = down_mutex & mutex : 0;
  put_forks = up_mutex : 1;
  1 : mutex;
  esac;
init (states[i]) := THINKING;
next (states[i]) := case
  take_forks = state_hungry : HUNGRY;
  take_forks = state_eating : EATING;
  put_forks = state_thinking : THINKING;
  1 : states[i];
  esac;
init (sems[i]) := 0;
next (sems[i]) := case
  take_forks = up_sem : 1;
  take_forks = down_sem & sems[i] : 0;
  1 : sems[i];
  esac;
```

SMV : Model : Philosopher : take_forks

```
init (take_forks) := begin;
next (take_forks) := case
  insns = take_forks_ &
  take_forks = begin : down_mutex;
  take_forks = down_mutex & mutex : state_hungry;
  take_forks = state_hungry : if;
  take_forks = if & (states[i] = HUNGRY &
    states[left] != EATING & states[right] != EATING) :
 state_eating;
  take_forks = if & !(states[i] = HUNGRY &
    states[left] != EATING & states[right] != EATING) :
 up_mutex;
  take_forks = state_eating : up_sem;
  take_forks = up_sem : up_mutex;
  take_forks = up_mutex : down_sem;
  take_forks = down_sem & sems[i] : end;
  take_forks = end : begin;
  1 : take_forks;
  esac;
```

SMV : Model : Philosopher : put_forks

```
init (put_forks) := begin;
next (put_forks) := case
  insns = put_forks_ &
  put_forks = begin : down_mutex;
  put_forks = down_mutex & mutex : state_thinking;
  put_forks = state_thinking : left_if;
  put_forks = left_if &  (states[left] = HUNGRY &
    states[leftleft] != EATING & states[leftright] != EATING) :
    left_state_eating;
  put_forks = left_if & !(states[left] = HUNGRY &
    states[leftleft] != EATING & states[leftright] != EATING) :
    right_if;
  put_forks = left_state_eating : left_up_sem;
  put_forks = left_up_sem : right_if;
  put_forks = right_if &  (states[right] = HUNGRY &
    states[rightleft] != EATING & states[rightright] != EATING) :
    right_state_eating;
  put_forks = right_if & !(states[right] = HUNGRY &
    states[rightleft] != EATING & states[rightright] != EATING) :
    up_mutex;
  put_forks = right_state_eating : right_up_sem;
  put_forks = right_up_sem : up_mutex;
  put_forks = up_mutex : end;
  put_forks = end : begin;
  1 : put_forks;
  esac;
```

SMV : Model : Philosopher : left, right

```
next (states[left]) := case
   put_forks = left_state_eating : EATING;
   1 : states[left];
   esac;
 next (states[right]) := case
   put_forks = right_state_eating : EATING;
   1 : states[right];
   esac;
 next (sems[left]) := case
   put_forks = left_up_sem : 1;
   1 : sems[left];
   esac;
 next (sems[right]) := case
   put_forks = right_up_sem : 1;
   1 : sems[right];
   esac;
```

SMV : Model : Philosopher : test

```
init (insns) := thinking_;
next (insns) := case
  insns = thinking_ : take_forks_;
  insns = take_forks_ & take_forks = end : eating_;
  insns = eating_ : put_forks_;
  insns = put_forks_ & put_forks = end : thinking_;
  1 : insns;
  esac;
```

SMV : Checking : 5

```
-- specification AG (AF ph_0.eating & AF ph_1.eating & AF... is true
-- specification AG ((ph_0.eating -> !ph_4.eating & !ph_1... is true
-- specification AG (EF (ph_0.eating & ph_2.eating) & EF ... is true

resources used:
user time: 44.68 s, system time: 0.38 s
BDD nodes allocated: 268703
Bytes allocated: 5439488
BDD nodes representing transition relation: 45646 + 52
reachable states: 149494 (2^17.1897) out of 1.51447e+17 (2^57.0716)
```

SMV : Checking : 4

```
-- specification AG (AF ph_0.eating & AF ph_1.eating & AF... is true
-- specification AG ((ph_0.eating -> !ph_3.eating & !ph_1... is true
-- specification AG (EF (ph_0.eating & ph_2.eating) & EF ... is true

resources used:
user time: 2.98 s, system time: 0.01 s
BDD nodes allocated: 127874
Bytes allocated: 3211264
BDD nodes representing transition relation: 29363 + 42
reachable states: 16450 (2^14.0058) out of 6.37405e+13 (2^45.8573)
```

Java : Overview

- Implemented the pseudocode
  - 4 classes, 100 LOC
  - Used semaphore class from
    - http://www.dcs.napier.ac.uk/~shaun/rtse/labs/lab04.html
- Tested with 5, 10, and 100 philosophers for 10K cycles
  - When a philosopher was eating, its neighbors weren't
    - Exclusive use of resources

Java : Shared Variables Class : 5

```
/**
 * Shared class so don't have to pass arguments to Philosopher
   objects.
 */
class Shared {

  final static int THINKING = 0;
  final static int HUNGRY = 1;
  final static int EATING = 2;

  final static int NUM_PS = 5;

  final static Semaphore mutex = new Semaphore (1);
  final static Philosopher p[] = new Philosopher[NUM_PS];
  final static Semaphore[] sems = new Semaphore[NUM_PS];
  final static int[] state = new int[NUM_PS];

  final static int NUM_CYCLES = 10000; //TESTING
  final static boolean[] isEating = new boolean[NUM_PS]; //TEST
  final static Thread[] threads = new Thread[NUM_PS]; //TEST
}
```

Java : Dining Philosophers “Main” Class

```
/**
 * Initialize all shared variables.  Start Philosopher threads.
 */
public class DiningPhilosophers extends Shared {

  public static void main(String[] argv) {

    for (int i = 0; i < NUM_PS; i++) {
      sems[i] = new Semaphore (0);
      state[i] = THINKING;
      p[i] = new Philosopher (i);
    }

    for (int i = 0; i < NUM_PS; i++) (threads[i] = new Thread
   (p[i])).start();
  }
}
```

Java : Source : Philosopher “Thread” Class : Overview

```
/**
 * Philosopher thread.
 */
class Philosopher extends Shared implements Runnable {

  private int id;

  Philosopher (int i) {
    id = i;
  }

  /**
   * Executed when thread is started.
   */
  public void run() {
     for (int i = 0; i < NUM_CYCLES; ++i) {
      think();
      take_forks();
      eat();
      put_forks();
    }
    System.out.println ("Philosopher " + id + " done.");  //TEST
  }
  ...
}
```

Java : Source : Philosopher “Thread” Class : *_forks()

```
private void take_forks() {
   mutex.down();
   state[id] = HUNGRY;
   test(id);
   mutex.up();
   sems[id].down();
 }

 private void put_forks() {
   mutex.down();
   state[id] = THINKING;
   test (LEFT(id));
   test (RIGHT(id));
   mutex.up();
 }
```

Java : Source : Philosopher “Thread” Class : Other

```
private void think() {}

private void eat() {
  //TEST: Everything below is for testing only
  isEating[id] = true;
  threads[id].yield();  //yield so other threads try to enter, good test
  if (isEating[LEFT(id)] || isEating[RIGHT(id)]) {  //exit if error
    System.out.println ("Error, neighbors should not eat right now! " +
      LEFT(id) + " " + id + " " + RIGHT(id));
    System.exit(0);
  }
  isEating[id] = false;
}

private void test (int i) {
  if (state[i]==HUNGRY && state[LEFT(i)]!=EATING &&
 state[RIGHT(i)]!=EATING) {
    state[i] = EATING;
    sems[i].up();
  }
}

private int LEFT (int i) {return (i + NUM_PS - 1) % NUM_PS;}

private int RIGHT (int i) {return (i + 1) % NUM_PS;}
```

Java : Source : Semaphore Class

```
/**
 * Semaphore class.
 * Taken from http://www.dcs.napier.ac.uk/~shaun/rtse/labs/lab04.html
 */
class Semaphore {

  private int count;

  Semaphore (int n) {
    this.count = n;
  }

  synchronized void down() {
    while(count == 0) {
      try {wait();}  //sleeps until notify() is called
      catch (InterruptedException e) {}
    }
    count--;
  }

  synchronized void up() {
    count++;
    notify(); //wakeup first thread that is blocking
  }
}
```

Java : Test : 5, 10, 100

Java : Test : 5

```
Philosopher 0 done.
Philosopher 2 done.
Philosopher 4 done.
Philosopher 1 done.
Philosopher 3 done.
```

Java : Test : 10

```
Philosopher 0 done.
Philosopher 1 done.
Philosopher 3 done.
Philosopher 5 done.
Philosopher 7 done.
Philosopher 2 done.
Philosopher 4 done.
Philosopher 6 done.
Philosopher 8 done.
Philosopher 9 done.
```

Java : Test : 100

```
Philosopher 73 done.
Philosopher 75 done.
Philosopher 77 done.
Philosopher 79 done.
Philosopher 71 done.
Philosopher 67 done.
Philosopher 0 done.
Philosopher 2 done.
Philosopher 65 done.
…
Philosopher 80 done.
Philosopher 82 done.
Philosopher 84 done.
Philosopher 86 done.
Philosopher 88 done.
Philosopher 90 done.
Philosopher 92 done.
Philosopher 94 done.
Philosopher 96 done.
Philosopher 98 done.
```