Formal Methods for Software Development
Introduction to Promela

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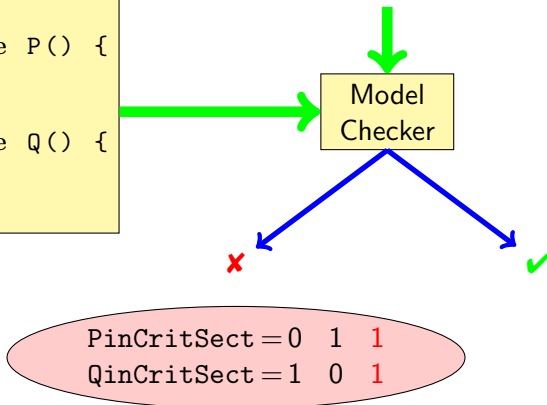03 September 2020

Towards Model Checking

System Model

Promela Program

```
byte n = 0;
active proctype P() {
  ...
}
active proctype Q() {
  ...
}
```

System Property

P, Q are never in their
critical section at the same time

Model
Checker

✗   ✔

PinCritSect = 0   1   1
QinCritSect = 1   0   1

What is PROMELA?

PROMELA **is an acronym**

PROcess MEta-LAnguage

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PROMELA **is an acronym**

PRO**cess** ME**ta-**LA**nguage**

PROMELA **is a language for modeling concurrent systems**
- ▶ multi-threaded

What is PROMELA**?**

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PROMELA **is a language for modeling concurrent systems**

▶ multi-threaded

▶ shared memory as well as message passing

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PROMELA **is a language for modeling concurrent systems**

▶ multi-threaded

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▶ few control structures, pure (side-effect free) expressions

What is PROMELA**?**

PROMELA **is an acronym**

PRO**cess** ME**ta-**LA**nguage**

PROMELA **is a language for** **modeling** **concurrent systems**

- ▶ multi-threaded
- ▶ shared memory as well as message passing
- ▶ few control structures, pure (side-effect free) expressions
- ▶ data structures with fixed bounds

What is PROMELA **Not?**

PROMELA **is not a programming language**

Very small language, not intended to program deployable systems.
(We will master most of it in today's lecture!)

▶ No pointers/references
▶ No procedures/methods/functions
▶ No libraries
▶ No input(!)
▶ No floating-point types
▶ Very limited structured types
▶ No data encapsulation

What is PROMELA **Not**?

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> Very small language, not intended to program deployable systems.
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> ▶ No pointers/references
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> ▶ No libraries
> ▶ No input(!)
> ▶ No floating-point types
> ▶ Very limited structured types
> ▶ No data encapsulation
> ▶ Nondeterministic

A First PROMELA Program

```
active proctype P() {
  printf("Hello world\n")
}
```

Command Line Execution

Simulating (i.e., interpreting) a PROMELA *program*

```
> spin hello.pml
      Hello world
1 process created
```

A First PROMELA Program

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Command Line Execution

Simulating (i.e., interpreting) a PROMELA *program*

```
> spin hello.pml
      Hello world
1 process created
```

- ▶ keyword **proctype** declares process named P
- ▶ keyword **active** creates one instance of P
- ▶ C-like command and expression syntax
- ▶ no ";" needed here (only for sequencing of commands)
- ▶ C-like (simplified) formatted print

Arithmetic Data Types

```
active proctype P() {
    int val = 123;
    int rev;
    rev = (val % 10) * 100 + /* % is modulo */
          ((val / 10) %  10) * 10 + (val / 100);
    printf("val␣=␣%d,␣rev␣=␣%d\n", val, rev)
}
```

Arithmetic Data Types

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active proctype P() {
    int val = 123;
    int rev;
    rev = (val % 10) * 100 + /* % is modulo */
          ((val / 10) %  10) * 10 + (val / 100);
    printf("val␣=␣%d,␣rev␣=␣%d\n", val, rev)
}
```

Observations

▶ Data types **byte**, **short**, **int**, **unsigned** with operations +,-,*,/,%

▶ Expressions computed as **int**, then converted to container type

▶ No floats, no side effects, C/Java-style comments

▶ No string variables (strings only in print statements)

Booleans and Enumerations

```
bit   b1 = 0;
bool b2 = true;
```

Observations

▶ bit numeric type containing 0, 1

▶ bool, true, false syntactic sugar for bit, 1, 0

Enumerations

```
mtype = { red , yellow , green } //in global context

active proctype P () {
  mtype light = green ;
  printf ("the light is %e\n", light )
}
```

Observations
- ▶ Literals represented as non-0 **byte**: at most 255
- ▶ **mtype** stands for message type (first used for message names)
- ▶ There is at most one **mtype** per program
- ▶ %e "prints" mtype value

Control Statements

Sequence	using ; as *separator*
	(not terminator like in C/Java)
Goto	jump to a label
Guarded Commands:	
— Selection	non-deterministic choice of an alternative
— Repetition	loop until `break` (or forever),
	non-deterministic choice of an alternative

Guarded Commands: Selection

```
active proctype P() {
  byte a = 5, b = 5;
  byte max, branch;
  if
    :: a >= b -> max = a; branch = 1
    :: a <= b -> max = b; branch = 2
  fi
}
```

Guarded Commands: Selection

```
active proctype P() {
  byte a = 5, b = 5;
  byte max, branch;
  if
    :: a >= b -> max = a; branch = 1
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```
Poll

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  byte a = 5, b = 5;
  byte max, branch;
  if
    :: a >= b -> max = a; branch = 1
    :: a <= b -> max = b; branch = 2
  fi
}
```

Poll

Command Line Execution

Trace of *random simulation* of multiple runs

```
> spin -v max.pml
> spin -v max.pml
> ...
```

Guarded Commands: Selection

```
active proctype P() {
  byte a = 5, b = 5;
  byte max, branch;
  if
    :: a >= b -> max = a; branch = 1
    :: a <= b -> max = b; branch = 2
  fi
}
```

Poll

Observations

▶ Each alternative starts with a guard (here a >= b, a <= b)

▶ Guards may "overlap" (more than one can be true at the same time)

▶ An alternative whose guard is true is randomly selected

▶ When *no* guard is true: process blocks until any becomes true

▶ if statements can have any number of alternatives

Guarded Commands: Selection Cont'd

```
bool p ;                              bool p ;
. . .                                 . . .
if                                    if
  : : p    -> . . .                     : : p    -> . . .
  : : true -> . . .                     : : else -> . . .
fi                                    fi
```

Guarded Commands: Selection Cont'd

```
bool p;                          bool p;
...                              ...
if                               if
  :: p    -> ...                   :: p    -> ...
  :: true -> ...                   :: else -> ...
fi                               fi
```

- ▶ Instance of the general case
- ▶ **true** can be selected
  anytime, regardless of other
  guards

Guarded Commands: Selection Cont'd

```
bool p ;
...
if
  :: p    -> ...
  :: true -> ...
fi
```

- Instance of the general case
- true can be selected anytime, regardless of other guards

```
bool p ;
...
if
  :: p    -> ...
  :: else -> ...
fi
```

- Special case
- else selected only if all other guards are false

Guarded Statement Syntax

```
:: guard -> command
```

Observations

- ▶ `->` is synonym for `;`
- ▶ Therefore: can use `;` instead of `->`
  (Relation guards vs. statements will get clearer later)
- ▶ First statement after `::` used as guard
- ▶ `-> command` can be omitted

Guarded Statement Syntax

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- ► Therefore: can use `;` instead of `->`
  (Relation guards vs. statements will get clearer later)
- ► First statement after `::` used as guard
- ► `-> command` can be omitted
- ► ("`->`" overloaded, see conditional expressions)

Guarded Commands: Repetition

```
active proctype P() { /* computes gcd */
  int a = 15, b = 20;
  do
    :: a > b -> a = a - b
    :: b > a -> b = b - a
    :: a == b -> break
  od
}
```

Guarded Commands: Repetition

```
active proctype P() { /* computes gcd */
  int a = 15, b = 20;
  do
    :: a > b -> a = a - b
    :: b > a -> b = b - a
    :: a == b -> break
  od
}
```

Command Line Execution

Trace with *values* of (local) variables

```
> spin -p -l gcd.pml
> spin --help
```

Guarded Commands: Repetition

```promela
active proctype P() { /* computes gcd */
  int a = 15, b = 20;
  do
    :: a > b -> a = a - b
    :: b > a -> b = b - a
    :: a == b -> break
  od
}
```

Observations

- ▶ An alternative whose guard is true is randomly selected
- ▶ Only way to exit loop is via **break** or **goto**
- ▶ When no guard true: loop blocks until one becomes true

Counting Loops

Counting loops can be realized with **break** after termination condition

```
#define N 10 /* C-style preprocessing */

active proctype P() {
  int sum = 0; byte i = 1;
  ...
  do
    :: i > N -> break                  /* test */
    :: else -> sum = sum + i; i++      /* body, increase */
  od
  ...
}
```

Counting Loops

Counting loops can be realized with **break** after termination condition

```
#define N 10 /* C-style preprocessing */

active proctype P() {
  int sum = 0; byte i = 1;
  ...
  do
    :: i > N -> break                /* test */
    :: else -> sum = sum + i; i++ /* body,increase */
  od
  ...
}
```

Observations
- ▶ Don't forget **else**, otherwise strange behaviour

For-loops

Since SPIN 6, support for native `for`-loops.

```
byte i;
for (i : 1..10) {
  /* loop body */
}
```

For-loops

Since SPIN 6, support for native `for`-loops.

```
byte i;
for (i : 1..10) {
  /* loop body */
}
```

Internally translated to:

```
byte i;
i = 1;
do
  :: i <= 10 ->
     /* loop body */
     i++
  :: else -> break
od
}
```

Awareness of translation helps when analyzing runs and interleavings.

Arrays

```
active proctype P() {
  byte a[5]; /* declare + initialize byte array a */
  a[0]=0; a[1]=10; a[2]=20; a[3]=30; a[4]=40;
  byte sum = 0, i = 0;
  do
    :: i == 5 -> break
    :: else   -> sum = sum + a[i]; i++
  od
}
```

Arrays

```
active proctype P() {
  byte a[5]; /* declare + initialize byte array a */
  a[0]=0; a[1]=10; a[2]=20; a[3]=30; a[4]=40;
  byte sum = 0, i = 0;
  do
    :: i == 5 -> break
    :: else   -> sum = sum + a[i]; i++
  od
}
```

Observations

- Arrays are scalar types: a and b always different arrays
- Array bounds are constant and cannot be changed
- Only one-dimensional arrays (there is an ugly workaround)

Record Types

```
typedef DATE {
  byte day, month, year;
}
active proctype P() {
  DATE D;
  D.day = 23; D.month = 5; D.year = 67
}
```

Record Types

```
typedef DATE {
  byte day, month, year;
}
active proctype P() {
  DATE D;
  D.day = 23; D.month = 5; D.year = 67
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```

Observations

▶ may include previously declared record types, but no self-references

Record Types

```
typedef DATE {
  byte day, month, year;
}
active proctype P() {
  DATE D;
  D.day = 23; D.month = 5; D.year = 67
}
```

Observations

- ▶ may include previously declared record types, but no self-references
- ▶ Can be used to realize multi-dimensional arrays:

  ```
  typedef VECTOR {
    int vec[10]
  }
  VECTOR matrix[5]; /* base type array in record */
  matrix[3].vec[6] = 17;
  ```

Jumps

```
#define N 10
active proctype P() {
   int sum = 0; byte i = 1;
   do
     :: i > N -> goto exitloop
     :: else -> sum = sum + i; i++
   od;
exitloop:
   printf("End of loop")
}
```

Jumps

```
#define N 10
active proctype P() {
  int sum = 0; byte i = 1;
  do
    :: i > N -> goto exitloop
    :: else -> sum = sum + i; i++
  od;
exitloop:
  printf("End of loop")
}
```

Observations

▶ Jumps allowed only within a process

▶ Labels must be unique for a process

▶ Can't place labels in front of guards (inside alternative ok)

▶ Easy to write messy model with **goto**

Inlining Code

PROMELA has no method or procedure calls

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```
typedef DATE {
  byte day, month, year;
}
inline setDate(D, DD, MM, YY) {
  D.day = DD; D.month = MM; D.year = YY
}
active proctype P() {
  DATE d;
  setDate(d,1,7,62)
}
```

Inlining Code

PROMELA has no method or procedure calls

```
typedef DATE {
  byte day, month, year;
}
inline setDate(D, DD, MM, YY) {
  D.day = DD; D.month = MM; D.year = YY
}
active proctype P() {
  DATE d;
  setDate(d,1,7,62)
}
```

- ▶ macro-like abbreviation mechanism for code that occurs multiply
- ▶ **inline** creates new scope for locally declared variables[a]
- ▶ but initializers moved outside the **inline** ⇒ use with care

---

[a]since SPIN 6, see [Ben-Ari, Supplementary Material on SPIN 6]

Non-Deterministic Programs

Deterministic PROMELA **programs are trivial**

Assume PROMELA program with one process and no overlapping guards

▶ All variables are (implicitly or explictly) initialized

▶ No user input possible

▶ Each state is either blocking or has exactly one successor state

Such a program has exactly one possible computation!

Non-Deterministic Programs

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- ▶ All variables are (implicitly or explictly) initialized
- ▶ No user input possible
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Such a program has exactly one possible computation!

Non-trivial PROMELA programs are non-deterministic!

Possible sources of non-determinism

1. Non-deterministic choice of alternatives with overlapping guards
2. Scheduling of concurrent processes

Non-Deterministic Generation of Values

```
byte x;
if
  :: x = 1
  :: x = 2
  :: x = 3
  :: x = 4
fi
```

Observations

- Assignment statement, used as guard,
    - enables its alternative,
    - performs the assigment as 'side effect'.

Non-Deterministic Generation of Values

```
byte x ;
if
   :: x = 1
   :: x = 2
   :: x = 3
   :: x = 4
fi
```

Observations

▶ Assignment statement, used as guard,
   ▶ enables its alternative,
   ▶ performs the assigment as 'side effect'.

▶ Example selects non-deterministically a value in $\{1, 2, 3, 4\}$ for x

Generation of values from explicit list impractical for large range

Non-Deterministic Generation of Values Cont'd

Generation of values from explicit list impractical for large range

```
#define LOW   0
#define HIGH 9
byte x = LOW;
do
   :: x < HIGH -> x++
   :: break
od
```

Non-Deterministic Generation of Values Cont'd

> Generation of values from explicit list impractical for large range

```
#define LOW   0
#define HIGH 9
byte x = LOW;
do
   :: x < HIGH -> x++
   :: break
od
```

Observations

- ▶ In each iteration, equal chance for increase of range and loop exit
- ▶ Chance of generating n in random simulation is $2^{-(n+1)}$
  - ▶ Obtain no representative test cases from random simulation.
  - ▶ OK for verification, because all computations are considered!

Select construct

Since SPIN 6, support for native select operator.

```
select(row : 1..8)
```

Select construct

Since SPIN 6, support for native `select` operator.

```
select(row : 1..8)
```

Internally translated to:

```
row = 1;
do
:: row < 8 -> row++
:: break
od
```

Awareness of translation helps when analyzing runs and interleavings.

Sources of Non-Determinism

1. Non-deterministic choice of alternatives with overlapping guards
2. Scheduling of concurrent processes

Concurrent Processes

```
active proctype P() {
  printf("Process P, statement 1\n");
  printf("Process P, statement 2\n")
}

active proctype Q() {
  printf("Process Q, statement 1\n");
  printf("Process Q, statement 2\n")
}
```

Concurrent Processes

```
active proctype P() {
  printf("Process␣P,␣statement␣1\n");
  printf("Process␣P,␣statement␣2\n")
}

active proctype Q() {
  printf("Process␣Q,␣statement␣1\n");
  printf("Process␣Q,␣statement␣2\n")
}
```

Observations

▶ Can declare more than one process (need unique identifier)

▶ SPIN allows at most 255 processes

Execution of Concurrent Processes

Command Line Execution

Random simulation of two processes

```
> spin interleave.pml
```

Execution of Concurrent Processes

Command Line Execution

Random simulation of two processes

```
> spin interleave.pml
```

Observations

- ▶ Scheduling of concurrent processes 'on one processor'
- ▶ Scheduler randomly selects process to make next step
- ▶ Many different computations are possible: non-determinism
- ▶ Use −p/−g/−l options to see more execution details

Sets of Processes

```
active [2] proctype P() {
  printf("Process %d, statement 1\n", _pid);
  printf("Process %d, statement 2\n", _pid)
}
```

Observations

▶ Can create set of identical processes

▶ Each process can have its own local variables

Sets of Processes

```
active [2] proctype P() {
  printf("Process %d, statement 1\n", _pid);
  printf("Process %d, statement 2\n", _pid)
}
```

Observations

▶ Can create set of identical processes

▶ Each process can have its own local variables

▶ Process identity stored in built-in, local variable `_pid`

Sets of Processes

```
active [2] proctype P() {
  printf("Process %d, statement 1\n", _pid);
  printf("Process %d, statement 2\n", _pid)
}
```

Observations

- ▶ Can create set of identical processes
- ▶ Each process can have its own local variables
- ▶ Process identity stored in built-in, local variable `_pid`

Command Line Execution

Random simulation of set of two processes

```
> spin interleave_set.pml
```

PROMELA **Computations**

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```
1 active [2] proctype P() {
2   byte n;
3   n = 1;
4   n = 2
5 }
```

PROMELA **Computations**

```
1 active [2] proctype P() {
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5 }
```

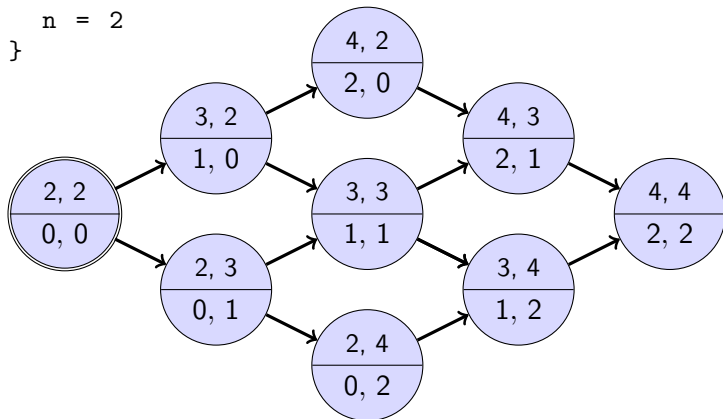> One possible computation ('run') of this model
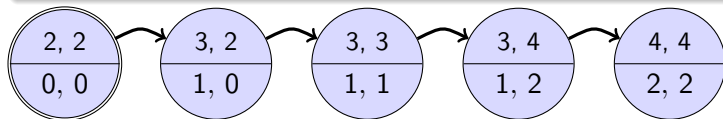
Notation
- ► Program pointer for each process in upper compartment
- ► Value of local n for each process in lower compartment

PROMELA **Computations**

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```

One possible computation ('run') of this model
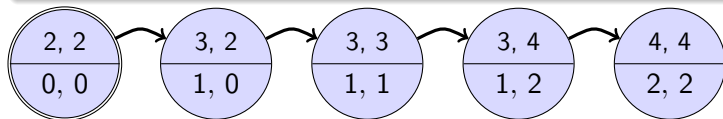
Notation

- ▶ Program pointer for each process in upper compartment
- ▶ Value of local n for each process in lower compartment

Computations are either infinite or terminating or blocking

Interleaving

```
1 active [2] proctype P() {
2   byte n;
3   n = 1;
4   n = 2
5 }
```

Atomicity

At which granularity of execution can interleaving occur?

Definition (Atomicity)

An expression or statement of a process that is executed entirely without the possibility of interleaving is called atomic.

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At which granularity of execution can interleaving occur?

Definition (Atomicity)

An expression or statement of a process that is executed entirely without the possibility of interleaving is called atomic.

Atomicity in PROMELA

▶ Assignments, jumps, skip, and expressions are atomic
  ▶ In particular, conditional expressions are atomic:
    (p -> q : r), C-style syntax, brackets required
▶ Guarded commands?

Atomicity Cont'd

Variables declared outside **proctype** are global.

Atomicity Cont'd

Variables declared outside `proctype` are global.

```
int a,b,c;
active proctype P() {
  a = 1; b = 1; c = 1;
  if
    :: a != 0 -> c = b / a
    :: else -> c = b
  fi
}
active proctype Q() { a = 0 }
```

Atomicity Cont'd

Variables declared outside `proctype` are global.

```
int a,b,c;
active proctype P() {
  a = 1; b = 1; c = 1;
  if
    :: a != 0 -> c = b / a
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```

Breakout

Atomicity Cont'd

Variables declared outside `proctype` are global.

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int a,b,c;
active proctype P() {
  a = 1; b = 1; c = 1;
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    :: a != 0 -> c = b / a
    :: else -> c = b
  fi
}
active proctype Q() { a = 0 }
```

Breakout

Command Line Execution

Particular interleaving enforced by interactive simulation

`> spin -p -g -i zero.pml`

Atomicity Cont'd

Atomicity in PROMELA

▶ Alternatives in guarded commands are not atomic

How to prevent interleaving?

1. Consider to use expression instead of selection statement:

   c = (a != 0 -> (b / a): b)

Atomicity Cont'd

Atomicity in PROMELA

▶ Alternatives in guarded commands are not atomic

How to prevent interleaving?

1. Consider to use expression instead of selection statement:

   `c = (a != 0 -> (b / a): b)`

2. Put code inside **atomic** (but potentally unfaithful model):

```
atomic {
if
  :: a != 0 -> c = b / a
  :: else -> c = b
fi
}
```

Atomicity Cont'd

Atomicity in PROMELA

▶ Alternatives in guarded commands are not atomic

How to prevent interleaving?

1. Consider to use expression instead of selection statement:

   `c = (a != 0 -> (b / a): b)`

2. Put code inside **atomic** (but potentally unfaithful model):

   ```
   atomic {
   if
     :: a != 0 -> c = b / a
     :: else  -> c = b
   fi
   }
   ```

   Remark: Blocking within **atomic** may lead to interleaving.
   atomic can lead to wrong modelling!

Usage Scenario of PROMELA

1. Model the essential features of a system in PROMELA
- ▶ abstract away, or simplify, complex (numeric) computations
  - ▶ make use of non-deterministic choice
- ▶ replace unbound data structures with fixed size date structures
- ▶ replace large variety by small variety

2. Select properties that the PROMELA model must satisfy
- ▶ Generic Properties (discussed in later lectures)
  - ▶ Mutual exclusion for access to critical resources
  - ▶ Absence of deadlock
  - ▶ Absence of starvation
  - ▶ Event sequences (e.g., system responsiveness)
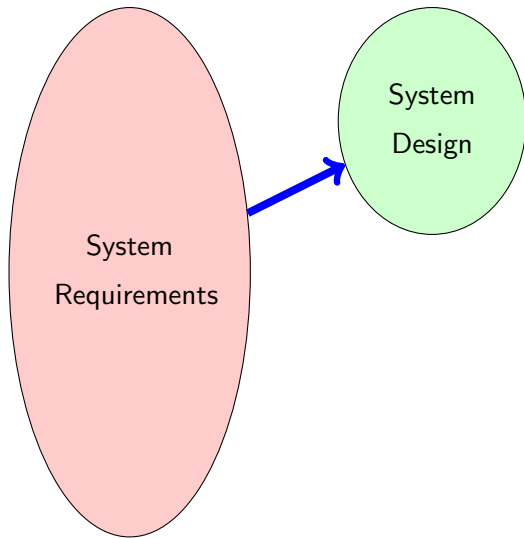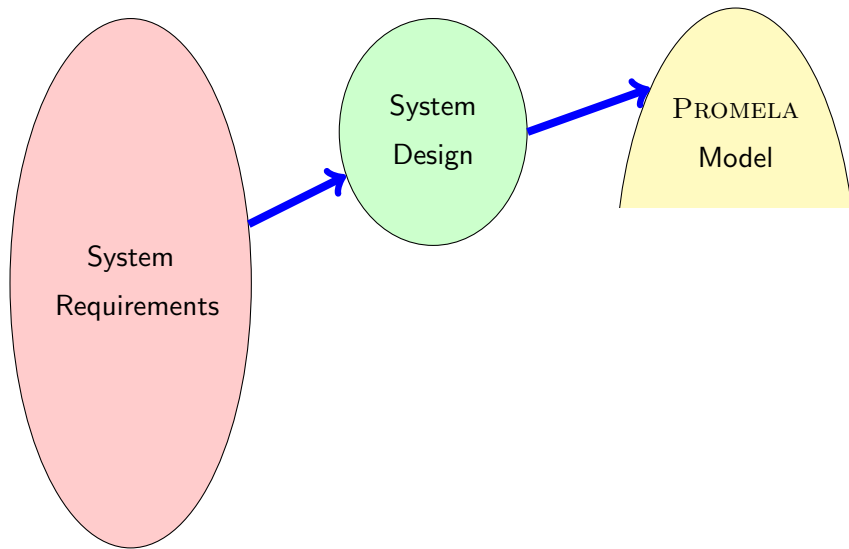- ▶ Specific Properties

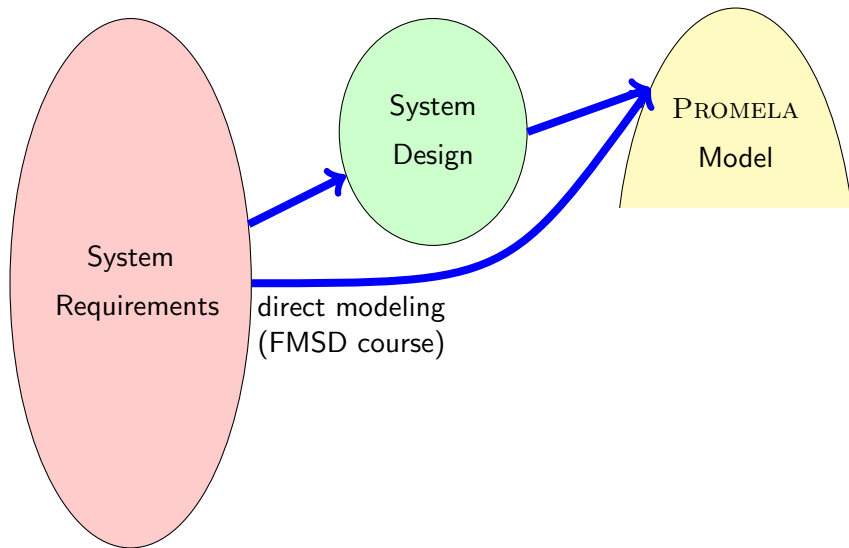# Formalisation with PROMELA
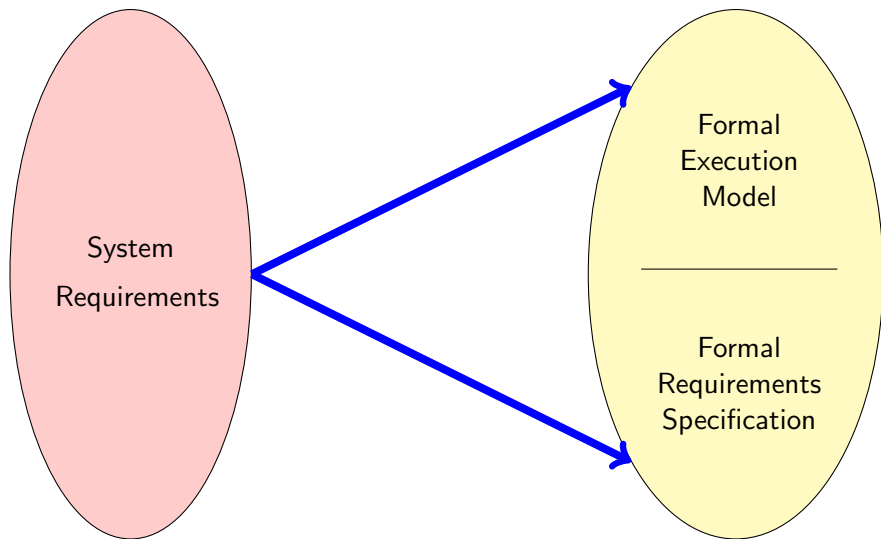
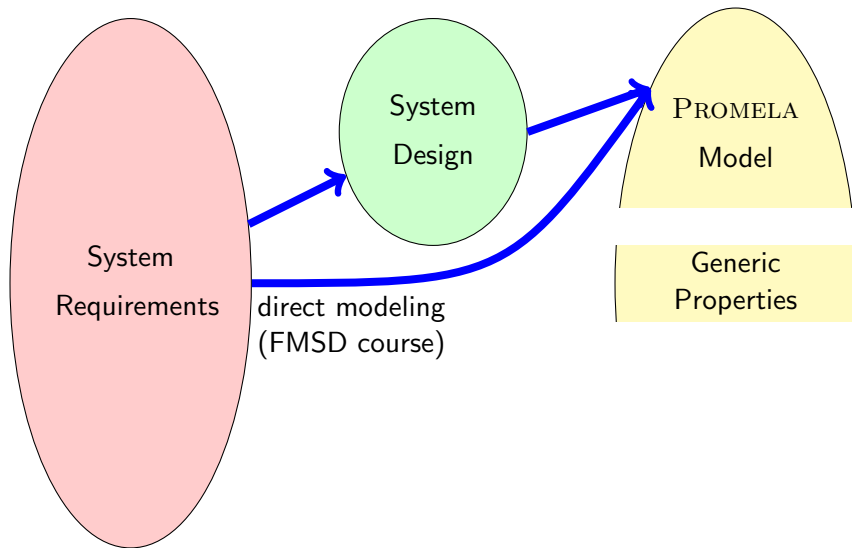# Formalisation with PROMELA
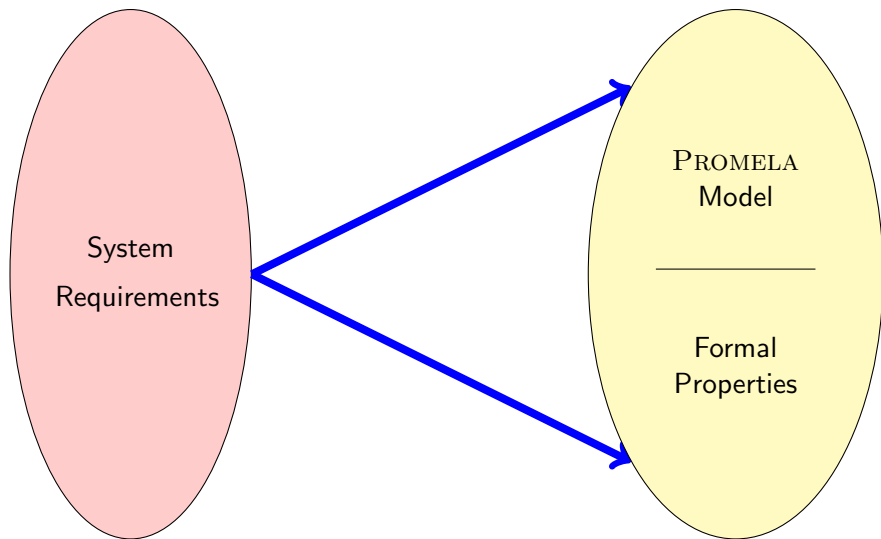
Formalisation with PROMELA
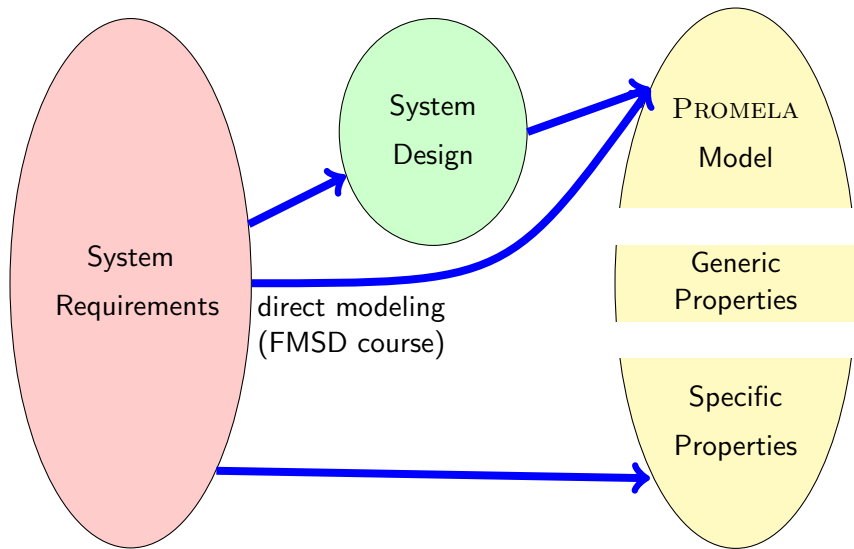
Formalisation with PROMELA **Abstraction**

Formalisation with PROMELA

Formalisation with PROMELA

System
Design

PROMELA
Model

System
Requirements

direct modeling
(FMSD course)

Generic
Properties

Specific
Properties

Usage Scenario of PROMELA **Cont'd**

1. Model the essential features of a system in PROMELA
   - abstract away from complex (numerical) computations
     - make use of non-deterministic choice
   - replace unbound data structures with fixed size date structures
   - replace large variety by small variety
2. Select properties that the PROMELA model must satisfy
   - Mutal exclusion for access to critical resources
   - Absence of deadlock
   - Absence of starvation
   - Event sequences (e.g., system responsiveness)
3. Verify that all possible runs of PROMELA model satisfy properties
   - Typically, need many iterations to get model and properties right
   - Failed verification attempts provide feedback via counter examples

Literature for this Lecture

Ben-Ari Chapter 1, Sections 3.1–3.3, 3.5, 4.6, Chapter 6

Ben-Ari-sup Supplementary Material on SPIN Version 6

Spin Reference card

jspin User manual, file `doc/jspin-user.pdf` in distribution