FORMAL METHODS IN NETWORKING

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LIGHTWEIGHT MODELING IN PROMELA/SPIN AND ALLOY

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LIGHTWEIGHT MODELING

DEFINITION

- constructing a very abstract model of the core concepts of a system
- using a "push-button" analysis tool to explore its properties

"analysis" is more general than "verification"

WHY IS IT "LIGHTWEIGHT"?

- because the model is very abstract in comparison to a real implementation, and focuses only on core concepts, it is small and can be constructed quickly
- because the analysis tool is "push-button", it yields results with little effort

in contrast, theorem proving is not "push-button"

WHAT IS ITS VALUE?

- it is a design tool that reveals conceptual errors early

decades of research on software engineering proves that the cost of fixing a bug rises exponentially with the delay in its discovery

- it is a documentation tool that provides complete, consistent, and unambiguous information to implementors and users
- it is easy (at least to get started) and fun!

"If you like surprises, you will love lightweight modeling."
—Pamela Zave

Read introduction to *Software Abstractions* for Daniel Jackson's view.

WHY IS LIGHTWEIGHT MODELING EASY, SURPRISING?

EASY + SURPRISING = FUN

PROGRAMMING:

1 write a program

2 think of a test case

3 run the program on the test that you thought of

LIGHTWEIGHT MODELING

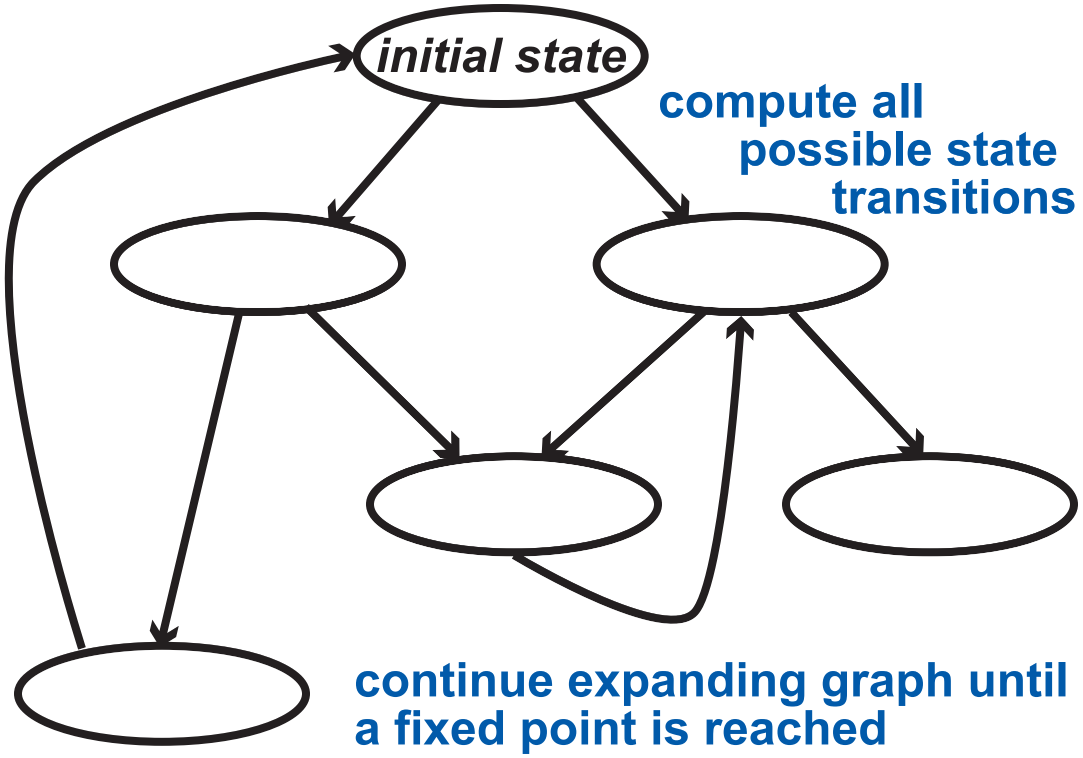
1 write a model (no bigger than a small program)

2 push the "analyze" button

3 get results from *all possible executions* in a particular category, including "tests" you would *never* have thought of!

HOW MODEL CHECKERS DO IT

all data structures have fixed size, so state space is bounded (includes implicit structures such as call stack)


initial state
compute all possible state transitions
continue expanding graph until a fixed point is reached

the result is an explicit, finite reachability graph representing all possible states, state transitions, and executions (finite or infinite paths through the graph)

WHAT IS THE HIDDEN CHALLENGE?

It is so easy to write a model, ask the analyzer a question, get an answer . . .

. . . but not so easy to know what any of these means in the real world.

NONDETERMINISM IN MODEL

- environment choice
- implementation freedom
- system failure
- concurrency

STATEMENTS IN MODEL

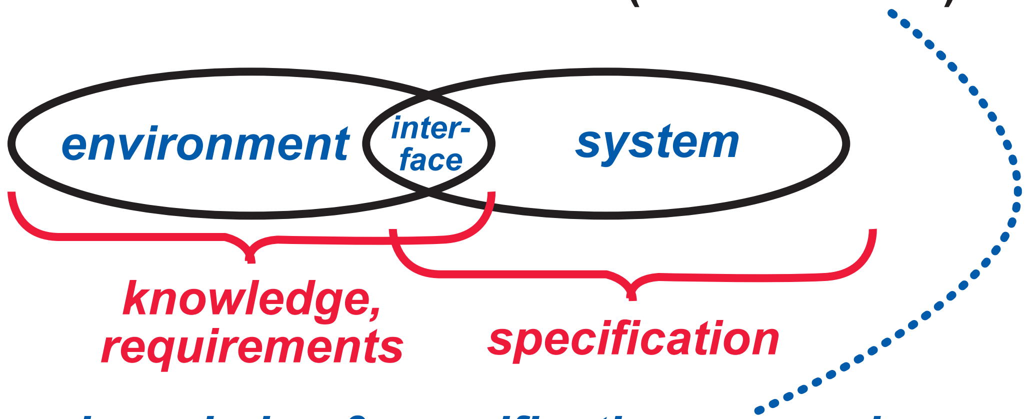
- domain knowledge: description of the environment in which the system will operate (fact or assumption)
- specification: an implementable description of how the hardware/software system should behave
- requirement: a description of how the environment should behave when the system is implemented and deployed
- sanity check: intended to be redundant

ANALYSIS QUESTIONS

- Is the model consistent (can be realized) ?
- Does the model mean what I think it means ("validation") ?

sanity checks help

- Is the model correct ("verification") ?



knowledge & specification => requirements

Read "Deriving specifications from requirements: An example" for an example with all the parts.

SPIN AND PROMELA

SPIN IS A MODEL CHECKER

- originated in the 1980's at Bell Labs
- freely available and actively maintained
- well-engineered and mature
- large user base, in both academia and industry
- used in mission-critical and safety-critical software development
- Spin user workshops have been held annually since 1995

Read CalTech lecture for Holzmann's introduction to model checking.

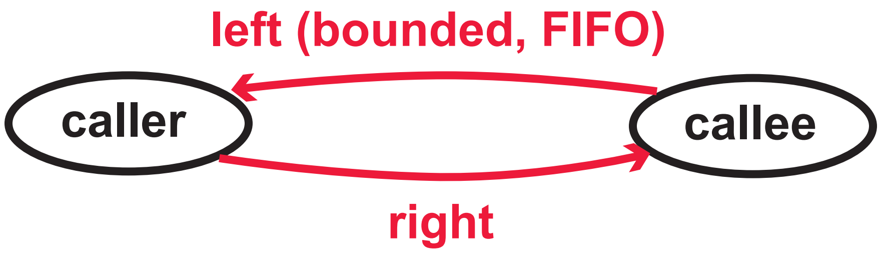
PROMELA IS ITS MODELING LANGUAGE

- unlike most mature model checkers, Spin is intended for software verification, not hardware verification
- "Promela" derived from "protocol modeling language"
- Promela resembles a primitive programming language
- it has built-in message queues for inter-process communication

Spin and other model checkers can also be used for verification of implementations, although that is not the focus here

SIP VERSION 1

```
mtype = { invite, accept, reject }
chan left = [3] of {mtype};
chan right = [3] of {mtype};
proctype caller (chan in, out) {
              out!invite;
inviting:     do
              :: in?accept; goto confirmed
              :: in?reject; goto end
              od;
confirmed:    do
              :: in?invite; out!accept
              :: out!invite; in?accept
              od;
end:          skip
}
proctype callee (chan in, out) {
              in?invite;
invited:      do
              :: out!accept; goto confirmed
              :: out!reject; goto end
              od;
confirmed:    do
              :: in?invite; out!accept
              :: out!invite; in?accept
              od;
end:          skip
}
init { atomic { run caller(left,right);
                run callee(right,left)
   }      }
```



do statement executes zero or more guarded commands

a guarded command can be executed only if its guard is true/executable

chan?mtype reads a message of type *mtype* from *chan*

executable iff. *chan* is not empty and its first message is of type *mtype*

chan!mtype writes a message of type *mtype* to *chan*

executable iff. *chan* is not full and holds messages of type *mtype*

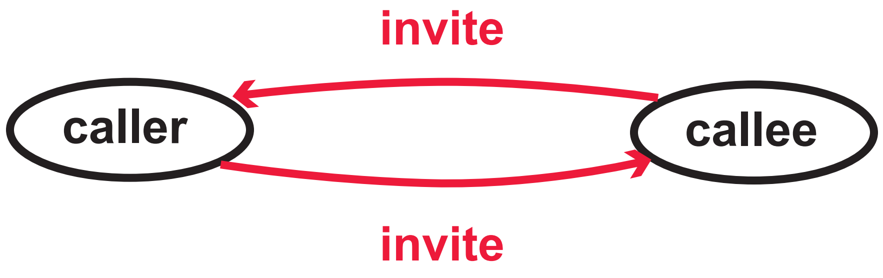
nondeterminism models:

environment choice
concurrency

SIP VERSION 1

```
mtype = { invite, accept, reject }
chan left = [3] of {mtype};
chan right = [3] of {mtype};
proctype caller (chan in, out) {
                out!invite;
inviting:   do
                :: in?accept; goto confirmed
                :: in?reject; goto end
                od;
confirmed:  do
                :: in?invite; out!accept
                :: out!invite; in?accept
                od;
end:        skip
}
proctype callee (chan in, out) {
                in?invite;
invited:    do
                :: out!accept; goto confirmed
                :: out!reject; goto end
                od;
confirmed:  do
                :: in?invite; out!accept
                :: out!invite; in?accept
                od;
end:        skip
}
init { atomic { run caller(left,right);
                    run callee(right,left)
    }       }
```

if both processes execute this statement at about the same time, they will deadlock



SIP VERSION 2

FIXES DEADLOCK DISCOVERED IN VERSION 1

```
mtype = { invite, accept, reject, race }
```

```
proctype caller (chan in, out) {
             out!invite;
inviting:    do
             :: in?accept; goto confirmed
             :: in?reject; goto end
             od;
confirmed:   do
             :: in?invite; out!accept
             :: out!invite; goto reInviting
             od;
reInviting:  do
             :: in?accept; goto confirmed
             :: in?race; goto confirmed
             :: in?invite; out!race
             od;
end:         skip
}
```

```
proctype callee (chan in, out) {
             in?invite;
invited:     do
             :: out!accept; goto confirmed
             :: out!reject; goto end
             od;
confirmed:   do
             :: in?invite; out!accept
             :: out!invite; goto reInviting
             od;
reInviting:  do
             :: in?accept; goto confirmed
             :: in?race; goto confirmed
             :: in?invite; out!race
             od;
end:         skip
}
```

until further notice, we are using only default analysis in Spin

neither process terminates, but analysis reports no errors because it is only looking for invalid end states

SIP VERSION 3

ADDS BYE AND ITS ACK TO END DIALOG

```
mtype = { invite, accept, reject, race, bye, byeAck }
```

```
proctype caller (chan in, out) {
             out!invite;
inviting:    do
             :: in?accept; goto confirmed
             :: in?reject; goto end
             od;
confirmed:   do
             :: in?invite; out!accept
             :: in?bye; out!byeAck; goto end
             :: out!invite; goto reInviting
             :: out!bye; goto end
             od;
reInviting:  do
             :: in?accept; goto confirmed
             :: in?race; goto confirmed
             :: in?invite; out!race
             od;
end:         skip
}
```

```
proctype callee (chan in, out) {
             in?invite;
invited:     do
             :: out!accept; goto confirmed
             :: out!reject; goto end
             od;
confirmed:   do
             :: in?invite; out!accept
             :: in?bye; out!byeAck; goto end
             :: out!invite; goto reInviting
             :: out!bye; goto end
             od;
reInviting:  do
             :: in?accept; goto confirmed
             :: in?race; goto confirmed
             :: in?invite; out!race
             od;
end:         skip
}
```

SIP VERSION 3

```
proctype caller (chan in, out) {
             out!invite;
inviting:    do
             :: in?accept; goto confirmed
             :: in?reject; goto end
             od;
confirmed:   do
             :: in?invite; out!accept
             :: in?bye; out!byeAck; goto end
             :: out!invite; goto reInviting
             :: out!bye; goto end
             od;
reInviting:  do
             :: in?accept; goto confirmed
             :: in?race; goto confirmed
             :: in?invite; out!race
             od;
end:         skip
}
```

```
proctype callee (chan in, out) {
             in?invite;
invited:     do
             :: out!accept; goto confirmed
             :: out!reject; goto end
             od;
confirmed:   do
             :: in?invite; out!accept
             :: in?bye; out!byeAck; goto end
             :: out!invite; goto reInviting
             :: out!bye; goto end
             od;
reInviting:  do
             :: in?accept; goto confirmed
             :: in?race; goto confirmed
             :: in?invite; out!race
             od;
end:         skip
}
```

if one of the processes is reInviting, and the first message in its input queue is bye, it will be blocked forever

SIP VERSION 4

FIXES BLOCKAGE IN VERSION 3

```
proctype caller (chan in, out) {
            out!invite;
inviting:   do
            :: in?accept; goto confirmed
            :: in?reject; goto end
            od;
confirmed:  do
            :: in?invite; out!accept
            :: in?bye; out!byeAck;
               goto end
            :: out!invite; goto reInviting
            :: out!bye; goto end
            od;
reInviting: do
            :: in?invite; out!race
            :: in?accept; goto confirmed
            :: in?race; goto confirmed
            :: in?bye; out!byeAck;
               goto end
            od;
end:        skip
}
```

```
proctype callee (chan in, out) {
            in?invite;
invited:    do
            :: out!accept; goto confirmed
            :: out!reject; goto end
            od;
confirmed:  do
            :: in?invite; out!accept
            :: in?bye; out!byeAck;
               goto end
            :: out!invite; goto reInviting
            :: out!bye; goto end
            od;
reInviting: do
            :: in?invite; out!race
            :: in?accept; goto confirmed
            :: in?race; goto confirmed
            :: in?bye; out!byeAck;
               goto end
            od;
end:        skip
}
```

SIP VERSION 4

```
proctype caller (chan in, out) {
             out!invite;
inviting:    do
             :: in?accept; goto confirmed
             :: in?reject; goto end
             od;
confirmed:   do
             :: in?invite; out!accept
             :: in?bye; out!byeAck;
                goto end
             :: out!invite; goto reInviting
             :: out!bye; goto end
             od;
reInviting:  do
             :: in?invite; out!race
             :: in?accept; goto confirmed
             :: in?race; goto confirmed
             :: in?bye; out!byeAck;
                goto end
             od;
end:         skip
}
```

```
proctype callee (chan in, out) {
             in?invite;
invited:     do
             :: out!accept; goto confirmed
             :: out!reject; goto end
             od;
confirmed:   do
             :: in?invite; out!accept
             :: in?bye; out!byeAck;
                goto end
             :: out!invite; goto reInviting
             :: out!bye; goto end
             od;
reInviting:  do
             :: in?invite; out!race
             :: in?accept; goto confirmed
             :: in?race; goto confirmed
             :: in?bye; out!byeAck;
                goto end
             od;
end:         skip
}
```

if a process sends a bye and ends, it may leave messages unread and unprocessed

"-q" runtime option makes an end state invalid if it has nonempty queues

SIP VERSION 5

GUARANTEES THAT BOTH PROCESSES ARE INPUT-ENABLED

in every state, a response to every message is defined

```
proctype caller (chan in, out) {
            out!invite;
inviting:   do
            :: in?invite; assert(false)
            :: in?accept; goto confirmed
            :: in?reject; goto end
            :: in?race; assert(false)
            :: in?bye; assert(false)
            :: in?byeAck; assert(false)
            od;
confirmed: do
            :: in?invite; out!accept
            :: in?accept; assert(false)
            :: in?reject; assert(false)
            :: in?race; assert(false)
            :: in?bye; out!byeAck;
               goto end
            :: in?byeAck; assert(false)
            :: out!invite; goto reInviting
            :: out!bye; goto Byeing
            od;
reInviting: do
            :: in?invite; out!race
            :: in?accept; goto confirmed
            :: in?reject; assert(false)
            :: in?race; goto confirmed
            :: in?bye; out!byeAck;
               goto end
            :: in?byeAck; assert(false)
            od;
Byeing:     do
            :: in?invite
            :: in?accept; assert(false)
            :: in?reject; assert(false)
            :: in?race; assert(false)
            :: in?bye; out!byeAck
            :: in?byeAck; goto end
            od;
end:        skip
}
```

assertions identify the inputs we do not expect—these are sanity checks

SIP VERSION 5

LOOKS BETTER WHEN UNREACHABLE CODE REMOVED

```
proctype caller (chan in, out) {
             out!invite;
inviting:    do
             :: in?accept; goto confirmed
             :: in?reject; goto end
             od;
confirmed: do
             :: in?invite; out!accept
             :: in?bye; out!byeAck;
                goto end
             :: out!invite; goto reInviting
             :: out!bye; goto Byeing
             od;
reInviting: do
             :: in?invite; out!race
             :: in?accept; goto confirmed
             :: in?race; goto confirmed
             :: in?bye; out!byeAck;
                goto end
             od;
Byeing:      do
             :: in?invite
             :: in?bye; out!byeAck
             :: in?byeAck; goto end
             od;
end:         skip
}
```

```
proctype callee (chan in, out) {
             in?invite;
invited:     do
             :: out!accept; goto confirmed
             :: out!reject; goto end
             od;
confirmed:  do
             :: in?invite; out!accept
             :: in?bye; out!byeAck;
                goto end
             :: out!invite; goto reInviting
             :: out!bye; goto Byeing
             od;
reInviting: do
             :: in?invite; out!race
             :: in?accept; goto confirmed
             :: in?race; goto confirmed
             :: in?bye; out!byeAck;
                goto end
             od;
Byeing:     do
             :: in?invite
             :: in?bye; out!byeAck
             :: in?byeAck; goto end
             od;
end:         skip
}
```