FORMAL METHODS IN NETWORKING

COMPUTER SCIENCE 598D, SPRING 2010

PRINCETON UNIVERSITY

LIGHTWEIGHT MODELING

IN PROMELA/SPIN AND ALLOY

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SIP VERSION 6

DOMAIN ASSUMPTION: a user process does not end the session until it has modified the session at least once

```
bool user1mod = false;
bool user2mod = false;

proctype user1 (chan in, out) {
   . . .
confirmed: do
        :: in?invite; out!accept
        :: in?bye; out!byeAck; goto end
        :: out!invite; goto reInviting
        :: user1mod;
           out!bye; goto Byeing
        od;
reInviting: do
        :: in?invite; out!race
        :: in?accept; user1mod = true;
           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:    assert(user1mod && user2mod) }
```

```
proctype user2 (chan in, out) {
   . . .
confirmed:  do
        :: in?invite; out!accept
        :: in?bye; out!byeAck; goto end
        :: out!invite; goto reInviting
        :: user2mod;
           out!bye; goto Byeing
        od;
reInviting: do
        :: in?invite; out!race
        :: in?accept; user2mod = true;
           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:    assert(user1mod && user2mod) }
```

REQUIREMENT: in every end state, each user has modified the session at least once

SIP VERSION 6

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```
bool user1mod = false;
bool user2mod = false;

proctype user1 (chan in, out) {
    . . .
confirmed: do
        :: in?invite; out!accept
        :: in?bye; out!byeAck; goto end
        :: out!invite; goto reInviting
        :: user1mod;
           out!bye; goto Byeing
        od;
reInviting: do
        :: in?invite; out!race
        :: in?accept; user1mod = true;
           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:    assert(user1mod && user2mod) }
```

```
proctype user2 (chan in, out) {
    . . .
confirmed:  do
        :: in?invite; out!accept
        :: in?bye; out!byeAck; goto end
        :: out!invite; goto reInviting
        :: user2mod;
           out!bye; goto Byeing
        od;
reInviting: do
        :: in?invite; out!race
        :: in?accept; user2mod = true;
           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:    assert(user1mod && user2mod) }
```

the assumption is not sufficient, because either user can end the session unilaterally, and the other user may not have acted yet

SIP VERSION 7

this version solves the problem by strengthening the domain assumption

```
bool user1mod = false;
bool user2mod = false;
```

these are global history variables—not easily implemented in a distributed system

they are used only to check that the specification satisfies a conditional requirement, so they will not be implemented!

```
proctype user1 (chan in, out) {
   . . .
confirmed: do
          :: in?invite; out!accept
          :: in?bye; out!byeAck; goto end
          :: out!invite; goto reInviting
          :: user1mod && user2mod;
             out!bye; goto Byeing
          od;
reInviting: do
          :: in?invite; out!race
          :: in?accept; user1mod = true;
             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:     assert(user1mod && user2mod) }
```

```
proctype user2 (chan in, out) {
   . . .
confirmed:  do
          :: in?invite; out!accept
          :: in?bye; out!byeAck; goto end
          :: out!invite; goto reInviting
          :: user2mod && user1mod;
             out!bye; goto Byeing
          od;
reInviting: do
          :: in?invite; out!race
          :: in?accept; user2mod = true;
             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:    assert(user1mod && user2mod) }
```

LIGHTNING OVERVIEW OF LINEAR-TIME TEMPORAL LOGIC (LTL)

LTL IS A LOGIC, I.E., A LANGUAGE OF TRUTH-VALUED FORMULAS

THE TRUTH OF AN LTL FORMULA IS DEFINED WITH RESPECT TO A STATE SEQUENCE (TRACE)

P	state predicate	*not temporal*	P ? . . .	(P true of first state in trace)
P U Q	P until Q	P and Q are mutually exclusive	Q ? . . . ; P . . . Q ? . . . , P . . . Q ? . . . ; P . . . Q ? . . .	(weak) (strong)
$\Box$ **P**	always P	*invariance*	P . . .	(P is true of every state in trace)
$\Diamond$ **P**	eventually P	*guarantee*	P ? . . . ; ? . . . P ? . . . ? P ?	(P is true of at least one state)
$\Box\Diamond$ **P**	always eventually P	*recurrence*	? . . . P ? . . . P . . . ? . . . P ? . . . P	(in every state, eventually P; if trace terminates, P is true in final state)
$\Diamond\Box$ **P**	eventually always P	*stability*	? . . . P . . .	(eventually, P becomes invariantly true)

LTL AND SPIN

LTL IS THE UNDERLYING MATHEMATICS OF SPIN

"SAFETY" PROPERTY

- usually, an invariance
- falsifiable by a finite trace prefix

"LIVENESS" OR "PROGRESS" PROPERTY

- contains a guarantee
- not falsifiable by a finite trace prefix

note: all real-time deadlines are safety properties

DEFAULT CHECKING IN SPIN

- specific invariances
- invalid end state:
  $\Box$! (terminal state &&
  process not in "end")
- assertion violation:
  $\Box$! (program counter at
  assertion && assertion
  not true in current state)
- requirement in SIP Versions 6 and 7 is a safety property, is not good enough because a user process could be starved forever

LTL CHECKING IN SPIN

- can check any temporal formula, including progress properties
- the SIP requirements we really want are:

  $\Box$ (user1tried —> $\Diamond$ user1mod)

  $\Box$ (user2tried —> $\Diamond$ user2mod)

the response pattern

SIP VERSION 8

$\Box$ (user1tried —> $\Diamond$ user1mod)
now holds for all traces

SIP guarantees a response to the caller (user1) by giving caller static priority

```
proctype user1 (chan in, out) {
    . . .
confirmed: do
        :: in?invite; out!accept
        :: in?bye; out!byeAck; goto end
        :: out!invite; user1tried = true;
           goto reInviting
        :: user1mod && user2mod;
           out!bye; goto Byeing
        od;
reInviting: do
        :: in?invite; out!race
        :: in?accept; user1mod = true;
           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 user2 (chan in, out) {
    . . .
confirmed:  do
        :: in?invite; out!accept
        :: in?bye; out!byeAck; goto end
        :: out!invite; user2tried == true;
           goto reInviting
        :: user2mod && user1mod;
           out!bye; goto Byeing
        od;
reInviting: do
        :: in?invite; out!accept
        :: in?accept; user2mod = true;
           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  }
```

SIP VERSION 8

SIP guarantees a response to the caller (user1) by giving caller static priority

$\Box$ (user2tried $\longrightarrow$ $\Diamond$ user2mod) is not true for all traces, detectable by means of a cycle in the reachability graph

```
proctype user1 (chan in, out) {
    . . .
confirmed: do
          :: in?invite; out!accept
          :: in?bye; out!byeAck; goto end
          :: out!invite; user1tried = true;
             goto reInviting
          :: user1mod && user2mod;
             out!bye; goto Byeing
          od;
reInviting: do
          :: in?invite; out!race
          :: in?accept; user1mod = true;
             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 user2 (chan in, out) {
    . . .
confirmed:  do
          :: in?invite; out!accept
          :: in?bye; out!byeAck; goto end
          :: out!invite; user2tried == true;
             goto reInviting
          :: user2mod && user1mod;
             out!bye; goto Byeing
          od;
reInviting: do
          :: in?invite; out!accept
          :: in?accept; user2mod = true;
             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  }
```

SIP VERSION 9

SIP implementations use timers to achieve specified behavior

now both processes are guaranteed a response

now user1 lets user2 in if it has lost a race

```
proctype user1 (chan in, out) {
   . . .
confirmed: do
        :: in?invite; out!accept;
           user2accepted = true
        :: in?bye; out!byeAck; goto end
        :: !user2lost || user2accepted;
           out!invite; user1tried = true;
           goto reInviting
        :: user1mod && user2mod;
           out!bye; goto Byeing
        od;
reInviting: do
        :: in?invite; out!race;
           user2lost = true
        :: in?accept; user1mod = true;
           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 user2 (chan in, out) {
   . . .
confirmed:  do
        :: in?invite; out!accept
        :: in?bye; out!byeAck; goto end
        :: out!invite; user2tried == true;
           goto reInviting
        :: user2mod && user1mod;
           out!bye; goto Byeing
        od;
reInviting: do
        :: in?invite; out!accept
        :: in?accept; user2mod = true;
           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  }
```

OTHER SPIN OPTIONS

SEARCH

- default search (traversal of reachability graph) is depth-first
- can search breadth-first
- can limit depth of search

there is a default of 10K, so you may have to increase limit

MEMORY—USUALLY THE SCARCEST RESOURCE

- default is 128 Mb
- can increase it by factors of 2
- compression saves memory with modest cost in time
- supertrace saves a lot of memory, but search is no longer complete

visited states are stored in a hash table, where multiple states may be indistinguishable

FEATURES I HAVE LITTLE USE FOR

- random or manual simulation mode (simulation guided by an error trail is essential!)
- turning off partial order reduction (an optimization that appears to have no disadvantages)
- weak fairness

probably too weak to make your model run correctly

how does an implementor implement a system whose specification is only correct with fairness built in?

strong fairness might make your model run correctly, but it is too expensive for Spin to offer

TALES OF SIP (THE SESSION INITIATION PROTOCOL)

SIP IS THE DOMINANT SIGNALING PROTOCOL FOR IP-BASED MULTIMEDIA APPLICATIONS

- telecommunications

voice-over-IP
video chat
large-scale conferencing
telemonitoring

- computer-supported cooperative work

embedded telecommunications
distance learning
emergency services
virtual reality

- computer-supported cooperative play

multiplayer games
collaborative television
networked music performance

SIP IS STANDARDIZED BY THE INTERNET ENGINEERING TASK FORCE (IETF)

- IETF philosophy is to standardize based on "rough consensus and working code"

- in the IETF, a finite-state machine is exotic

- IETF culture supports ignoring "corner cases"

a corner case is an unanticipated and undesirable situation, which is declared to be rare without evidence

- the IETF is dominated by equipment manufacturers, who do not want standards

they standardize only under pressure from their customers, and participate in the IETF as a highly competitive game

TALES OF SIP: THE PROTOCOL SPECIFICATION

SIP HAS BEEN, AND IS BEING, DEFINED BOTTOM-UP IN RESPONSE TO AN ENDLESS SERIES OF NEW USE CASES

- the base document (IETF RFC 3261) is 268 pages
- "A Hitchhiker's Guide to SIP" is a snapshot of SIP RFCs and drafts . . .

  . . . which lists **142** documents, totaling many thousands of pages

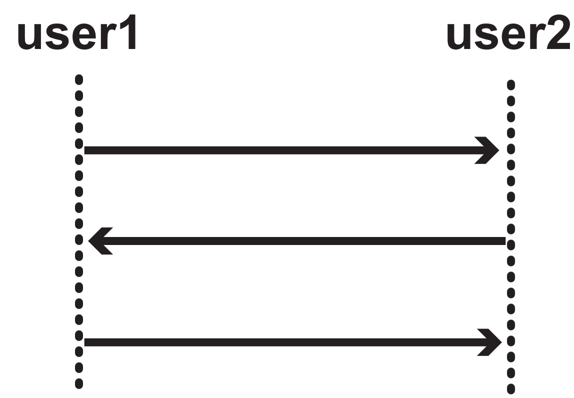
- everyone wants "simple SIP", and everyone has a different idea of what it should be
- opinions are based on a false opposition between generality and simplicity

  no conception that a protocol based on better abstractions could be both more general and simpler

- message overhead is too high

THE DOCUMENTS

- written in English, augmented only by message sequence charts that look like this (IETF macros):



compare these to the charts generated by Spin— these are inviting, almost forcing, you to think that network communication is instantaneous!

- not surprisingly, the standard is incomplete, inconsistent, or ambiguous in places

TALES OF SIP: USING PROMELA/SPIN

MODELING

- we have a collection of SIP models
- we are gradually increasing their scope (bigger subsets of protocol, endpoint/server configurations)

UNDERSTANDING SIP

- models show what an endpoint must do to use and interpret the protocol correctly—this is far more complicated than previously understood
- on TCP vs. UDP: with non-FIFO communication, the reachability graph is 100 times the size of the FIFO reachability graph
- an RFC documents 7 race conditions—our model reveals those and 49 others of the same type

DOCUMENTING SIP

- we annotate our models with pointers to the relevant sections of RFCs
- as documentation, our models are guaranteed to be complete, consistent, and unambiguous
- also, you know where to find the answer to your question!

OTHER USES OF MODEL CHECKING

- we verify the algorithms in our tools for SIP service creation, e.g., showing that media channels are controlled correctly
- we have modified Spin to generate test cases automatically; then we subject SIP components to thousands of tests with guaranteed coverage

EVALUATION OF PROMELA/SPIN

SPIN

- a powerful, industrial-strength tool
- mostly easy to use, with a few bad spots (horrible parser, false negatives in reporting unreachable code)

PROMELA

- great for temporal modeling and assertions
- great for message channels
- primitive data structures (bool, byte, mtype, int, array)
- primitive data assertions (==, <, <=, >, >= on values)

A SUGGESTED CLASS PROJECT

CREATE A MODEL OF TCP

- SYN, FIN, ACK messages to create and destroy connections
- DATA messages with sequence numbers
- model out-of-order message delivery
- model how TCP provides FIFO message streams in both directions, and use Spin to verify correctness

IF THAT WAS TOO EASY . . .

- also model message loss, show how TCP provides reliable, duplicate-free message streams in both directions, and use Spin to verify correctness