Software Engineering using Formal Methods

Modeling Distributed Systems

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This Lecture

You know you have a distributed system when the crash of a computer you've never heard of stops you from getting any work done. –*Leslie Lamport*

Using PROMELA channels for modeling distributed systems

Modeling Distributed Systems

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- nodes
- interacting via communication channels
- protocols dictate how nodes communicate with each other

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- interacting via communication channels
- protocols dictate how nodes communicate with each other

Distributed systems are very complex

Models of distributed systems abstract away from details of networks/protocols/nodes

In PROMELA:

- nodes modeled by PROMELA processes
- communication channels modeled by PROMELA channels
- protocols modeled by algorithm distributed over processes

Channels in PROMELA

In PROMELA, channels are first class citizens

Data type **chan** with two operations for sending and receiving

A variable of channel type is declared by initializer:

chan *name* = [*capacity*] **of** {$type_1, \ldots, type_n$}

name	name of channel variable
capacity	non-negative integer constant
$type_i$	PROMELA data types

Example:

chan `ch` = [2] **of** { **mtype**, **byte**, **bool** }

Meaning of Channels

chan *name* = [*capacity*] **of** {$type_1, ..., type_n$}

Creates channel, stored in *name*

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The channel has *no* buffer if $capacity = 0$
$\Rightarrow$ *"rendezvous channel"*

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Example:

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chan ch = [2] of { mtype, byte, bool }
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Given, e.g., **mtype** `= {red, yellow, green}`,
an example message on `ch` can be:

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Given, e.g., **mtype** = `{red, yellow, green}`,
an example message on `ch` can be: `green, 20,` **false**

`ch` is a *buffered channel*, buffering up to 2 messages

Sending and Receiving

send statement has the form:

$$name\ !\ expr_1, \ldots, expr_n$$

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- *assigns* values of message to var_1, ... , var_n
- example: `ch ? color, time, flash`

Client-Server

```
chan request = [0] of { byte };

active proctype Client0() {
  request ! 0
}

active proctype Client1() {
  request ! 1
}

...
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`Client0` and `Client1` send messages 0 and 1 to `request`

order of sending is nondeterministic

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active proctype Server() {
  byte num;
  do
    :: request ? num;
       printf("serving␣client␣%d\n", num)
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Server loops on:

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`Server` loops on:

- receiving first message from `request`, storing value in `num`
- printing

Demo

`rendezvous1`
random simulation

Executability of receive Statement (non-buffered)

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request ? num
```

executable only when another process offers send on channel `request`

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do
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Executability of receive Statement (non-buffered)

`request ? num`

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⇒ receive statement frequently used as guard in **if**/**do**-statements

```
do
  :: request ? num ->
       printf("serving␣client␣%d\n", num)
od
```

("->" equivalent to ";", but highlights guard role of `request ? num`)

Demo

`rendezvous1`
interactive simulation

Rendezvous Channels

```
chan ch = [0] of { byte, byte };

/* global to make visible in SpinSpider */
byte hour, minute;

active proctype Sender() {
  printf("ready\n");
  ch ! 11, 45;
  printf("Sent\n")
}

active proctype Receiver() {
  printf("steady\n");
  ch ? hour, minute;
  printf("Received\n")
}
```

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Which interleavings can occur?

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```

Which interleavings can occur? ⇒ ask SPINSPIDER

Demo

through jSpin:
SpinSpider on `ReadySteady.pml`

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Sender		Receiver
⋮		⋮
`(11,45)`	$\longrightarrow$	`(hour,minute)`
⋮		⋮

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in any cases:

location counter of both processes is incremented at once

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only place where PROMELA processes execute synchronously

Reconsider Client Server

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chan request = [0] of { byte };

active proctype Server() {
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  do :: request ? num ->
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active proctype Client0() {
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  request ! 1
}
```

so far no reply to clients

Reply Channels

```
chan request = [0] of { byte };
chan reply = [0] of { bool };

active proctype Server() {
  byte num;
  do :: request ? num ->
        printf("serving client %d\n", num);
        reply ! true
  od
}
active proctype Client0() {
  request ! 0;   reply ? _
}
active proctype Client1() {
  request ! 1;   reply ? _
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  od
}
active proctype Client0() {
  request ! 0;   reply ? _
}
active proctype Client1() {
  request ! 1;   reply ? _
}
```

(anonymous variable "_" used if interested in receipt, not content)

Reply Channels - Single Server

```
mtype = { nice , rude };
chan request = [0] of { mtype };
chan reply = [0] of { mtype };

active proctype Server() {
  mtype msg;
  do :: request ? msg; reply ! msg
  od
}
active proctype NiceClient() {
  mtype msg;
  request ! nice; reply ? msg;

}
active proctype RudeClient() {
  mtype msg;
  request ! rude; reply ? msg
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```

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Is the assertion valid?

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  mtype msg;
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}
```

Is the assertion valid? Ask SPIN.

Several Servers

More realistic with several servers:

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active [2] proctype Server() {
  mtype msg;
  do :: request ? msg; reply ! msg
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And here? Analyse with SPIN.

Sending Channels via Channels

To fix the protocol:

Sending Channels via Channels

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clients declare local reply channel + send it to server

Sending Channels via Channels

```
mtype = { nice, rude };
chan request = [0] of { mtype, chan };

active [2] proctype Server() {
  mtype msg; chan ch;
  do :: request ? msg, ch;
        ch ! msg
  od
}
active proctype NiceClient() {
  chan reply = [0] of { mtype };  mtype msg;
  request ! nice, reply;   reply ? msg;
  assert( msg == nice )
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active proctype RudeClient() {
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verify with Spin

Scope of Channels

channels are typically declared global

global channel

- usual case
- all processes can send and/or receive messages

local channel

- rarely used
- dies with its process
- can be useful to model security issues
  example:
  local channel could be passed
  through a global channel

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example, clients code:

```
chan reply = [0] of { byte, byte };
request ! _pid, reply;
reply ? serverID, clientID;
```

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example, clients code:

```
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request ! _pid, reply;
reply ? serverID, clientID;

assert( clientID == _pid )
```

Limitations of Rendezvous Channels

- rendezvous too restrictive for many applications
- servers and clients block each other too much
- difficult to manage uneven workload
  (online shop: dozens of webservers serve thousands of clients)

Buffered Channel

buffered channels queue messages;
requests/services no not immediately block clients/servers

example:

```
chan ch = [3] of { mtype, byte, bool }
```

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buffered channels, with capacity *cap*

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- can hold up to *cap* messages
- are a FIFO (first-in-first-out) data structure:
  always the 'oldest' message in channel is retrieved by a receive
- (normal) receive statement reads and removes message
- Sending and Receiving to/from buffered channels is asynchronous,
  i.e. interleaved

Executability of Buffered Channel operations

given channel `ch`, with capacity *cap*, currently containing *n* messages

receive statement `ch ? msg`

is executable iff `ch` is not empty, i.e., $n > 0$

send statement `ch ! msg`

is executable iff there is still 'space' in the message queue, i.e., $n < cap$

An non-executable receive or send statement will block until it is executable again

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(With option `-m`, Spin has a different send semantics:
attempt to send to a full channel does not block, but the message gets lost.)

Checking Channel for Full/Empty

this can save from unnecessary blocking:

given channel `ch`:

full(`ch`) checks whether `ch` is full
nfull(`ch`) checks whether `ch` is not full
empty(`ch`) checks whether `ch` is empty
nempty(`ch`) checks whether `ch` is not empty

illegal to negate those
avoid combining with **else**

Copy Message without Removing

Assume `ch` to be a buffered channel.

```
ch ? color, time, flash
```

- assigns values from the message to `color, time, flash`
- removes message from `ch`

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ch ? <color, time, flash>
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- assign values from the message to `color, time, flash`
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Dispatching Messages

Recurring task: Dispatch action depending on message

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```
mtype = {hi, bye};
chan ch = [0] of {mtype};

active proctype Server () {
   mtype msg;
read:
  ch ? msg;
  do
    ::  msg == hi -> printf("Hello.\n"); goto read
    ::  msg == bye -> printf("See␣you.\n"); break
  od
}
...
```

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Recurring task: Dispatch action depending on message

```
mtype = {hi, bye};
chan ch = [0] of {mtype};

active proctype Server () {
   mtype msg;
read:
  ch ? msg;
  do
    ::  msg == hi -> printf("Hello.\n"); goto read
    ::  msg == bye -> printf("See␣you.\n"); break
  od
}
...
```

There is a better way!

Pattern Matching

Receive statement allows also values as arguments:

$$ch \; ? \; exp_1, \ldots, exp_n$$

- $exp_1, \ldots, exp_n$ any(!) expressions of correct type
- statement is executable, iff message $msg_1, \ldots, msg_n$ in channel ch matches arguments, i.e. if
  - exp_i is a variable, then any value of msg_i (of correct type) matches and is assigned if statement is executed

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  - exp_i is a variable, then any value of msg_i (of correct type) matches and is assigned if statement is executed
  - exp_i is a value, e.g. 23, msg_i must have same value

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Dispatching Messages Revisited

Recurring task: Dispatch action depending on message type.

```
mtype = {hi, bye};
chan ch = [0] of {mtype};

active proctype Server () {
  int i;
  do
    :: ch ? hi  -> printf("Hello.\n")
    :: ch ? bye -> printf("See␣you.\n"); break
  od
}
...
```

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Random receive `??` (for buffered channels)

- Executable if matching message exists in channel.
- If executed, first matching message removed from channel.

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- If executed, first matching message removed from channel.

```
mtype = {hi, bye};
chan ch = [3] of {mtype};

active proctype Server () {
  int i;
  do
    :: ch ?? bye -> printf("See␣you.\n"); break
    :: else      -> printf("Hello.\n")
  od
}
...
```

Nicer Message Formatting

PROMELA provides an alternative, but equivalent syntax for

```
ch ! exp1, exp2, exp3
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```
ch ! exp1, exp2, exp3
```

namely

```
ch ! exp1(exp2, exp3)
```

Increases readability for certain applications, e.g. protocol modelling:

`ch!send(msg,id)`	vs.	`ch!send,msg,id`
`ch!ack(id)`	vs.	`ch!ack,id`

And finally

Buffered channels are part of the state!

State space gets much bigger using buffered channels

Use with care (and with small buffers).