Formal Methods for Software Development

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

Distributed systems consist of

- nodes,
- interacting via communication channels,
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- 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.

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A variable of channel type is declared by initializer:

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name	name of channel variable
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$type_i$	PROMELA data types

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Example:

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chan ch = [2] of { mtype, byte, bool }
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The channel has *no* buffer if $capacity = 0$
$\Rightarrow$ *"rendezvous channel"*

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an example message on `ch` can be:

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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
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active proctype Client1() {
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}

...
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Order of sending is nondeterministic

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active proctype Server() {
  byte num;
  do
    :: request ? num;
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  od
}
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Server loops on

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

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Executability of receive Statement (non-buffered)

`request ? num`

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

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

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

("->" equivalent to ";")

Rendezvous Channels

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

/* global only 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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On a rendezvous channel:

Transfer of message from sender to receiver is synchronous,
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Sender		Receiver
⋮		⋮
`(11,45)`	$\longrightarrow$	`(hour,minute)`
⋮		⋮

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In both case, the next step is:

Location counter of both processes is incremented in one step.

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Only place where 2 PROMELA processes execute at once

Reconsider Client Server

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chan request = [0] of { byte };

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

So far no reply to clients

Reply Channels

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

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

(Anonymous variable "_": data from message not stored anywhere)

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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Is the assertion valid? *Poll.*

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Is the assertion valid? *Poll.* *Ask* SPIN.

Several Servers

More realistic with several servers:

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Sending Channels via Channels

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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 )
}
active proctype RudeClient() {
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}
```

verify with SPIN

Scope of Channels

Global channel

- All processes can send and/or receive messages

Local channel

- Can model 'private' communication & security issues
- Example:
  Local channel can be passed through a global channel

Sending Process IDs

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Experiment with `rendezvous3.pml`

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Alternative:
Processes send their own, unique process ID, `_pid`, as part of message

Experiment with `rendezvous3.pml`

Example, clients code:

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

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- inflexible
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Alternative:
Processes send their own, unique process ID, `_pid`, as part of message

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Example, clients code:

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

assert( serversClient == _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 block clients/servers less often.

Example:

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

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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., $n < cap$

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

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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., $n < cap$

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

(With option `-m`, SPIN has a different send semantics:
Attempt to send to full channel doesn't block, but message gets lost.)

Checking Channel for Full/Empty

This can prevent 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`

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`

```
ch ? <color, time, flash>
```

- Assign values from the message to `color, time, flash`
- Leaves message in `ch`

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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    ::  msg == hi -> printf("Hello.\n"); goto read
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}
...
```

There is a better way!

Dispatching Messages

Recurring task: Dispatch action depending on message.

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

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

Note: `hi` and `bye` are *values*, not variables!

Pattern Matching

Receive statement allows also non-variable expressions as arguments:

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

- $exp_1, \ldots, exp_n$ any(!) expressions of correct type
- Receive statement is executable, iff
  - either of the following holds:
    - ch is buffered channel and not empty, or
    - ch is rendezvous channel and some process ready to send to ch
  - message $v_1, \ldots, v_n$ in channel ch matches $exp_1, \ldots, exp_n$
- v_i matches exp_i iff
  - exp_i is a variable and v_i a value (of correct type)
  - exp_i is not a variable and $exp_i == v_i$

Pattern Matching Examples

Assume

```
chan ch = [0] of {int, int};
int id = 5;
```

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Poll

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Does `ch ? 0, id` match message

- `[0, 5]` ?

Pattern Matching Examples

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Does `ch ? 0, id` match message

- `[0, 5]` ? ✔

Pattern Matching Examples

Assume

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

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Does `ch ? 0, id` match message

- [0, 5] ? ✔ [0, 7] ?

Pattern Matching Examples

Assume

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```

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Does `ch ? 0, id` match message

- `[0, 5]` ? ✔ `[0, 7]` ? ✔

Pattern Matching Examples

Assume

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chan ch = [0] of {int, int};
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Does `ch ? 0, id` match message

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Does `ch ? 0, id` match message

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- Value of `id` afterwards?

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- `[0, 5]` ? ✔   `[0, 7]` ? ✔   `[1, 7]` ? ✘
- Value of `id` afterwards?

To match the value stored in a variable *var* use `eval(var)`

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Does `ch ? 0, eval(id)` match message

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chan ch = [0] of {int, int};
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Poll

Does `ch ? 0, eval(id)` match message

- [0, 5] ? ✔ [0, 7] ? ✘ [1, 7] ? ✘
- Value of `id` afterwards?

Dispatching Messages Revisited

Random receive `??` (for buffered channels)

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

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

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

active proctype Server () {
  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).