- Developed at Bell Labs.
- In 2002, recognized by the ACM with *Software System Award* (like Unix, TeX, Smalltalk, Postscript, TCP/IP, Tcl/Tk).
- Automated tools convert programs written in Java or in C into SPIN models.
- The specification language is called PROMELA.
- SPIN has a graphical user interface, XSPIN.
- Homepage: `http://spinroot.com/spin/whatispin.html`
- Manual: `http://spinroot.com/spin/Man/index.html`

PROMELA

- PROMELA is suitable to describe concurrent software.
  - dynamic creation of concurrent processes
  - (synchronous/asynchronous) communication via message channels
- Programs written in PROMELA can be executed/simulated.
- *Simulation* shows one execution.
- *Verification* checks every execution.

Basic commands

- To simulate a program:

  ```
  spin system.pml
  ```

- Interactively:

  ```
  spin -i system.pml
  ```

- To generate a verifier (`pan.c`):

  ```
  spin -a system.pml
  ```

2 PROMELA examples

2.1 Hello world!

Hello world!

```
active proctype main()
{
        printf("hello world\n")
}
```

- **active** instantiates one process of the type that follows.
- **proctype** denotes that *main* is a process type.
- *main* identifies the process type, it's not a keyword.
- Note that ';' is missing after **printf**: ';' is a statement separator, not a statement terminator.

Remark

- Each process instance has a unique, positive instantiation number.
- A process-instance remains active until the process' body terminates (if ever).

Hello world! Alternative

```
init {
        printf("hello world\n")
}
```

- **init** is a process that initializes the system.
- Initially just the initial process is executed.

Simulation:

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

2.2 Producers/Consumers

Producers/Consumers

File `prodcons.pml`:

```
mtype = { P, C };

mtype turn = P;

active proctype producer()
{
        do
        :: (turn == P) ->
                printf("Produce\n");
                turn = C
        od
}
...
```

Producers/Consumers

- **mtype** defines symbolic values.
- *turn* is a global variable.
- **do ... od** (i.e. repetition statement) defines a loop.
- Only a `break` statement can break the loop.
- Every option of the loop must start with '`::`'.
- `(turn == P)` is the guard of the option.
- `->` and `;` are equivalent (`->` indicates a causal relation between successive statements).
- If all guards are false, then the process blocks.
- If multiple guards are true, we get non-determinism.

Producers/Consumers

The producer's definition is equivalent to:

```
active proctype producer()
{
again:  if
        :: (turn == P) ->
                printf("Produce\n");
                turn = C
        fi;
```

```
        goto again
}
```

- `goto` transfers control to the statement labeled by `again`.

Producers/Consumers

Also equivalent to:

```
active proctype producer()
{
again:  (turn == P) ->
                printf("Produce\n");
                turn = C;
        goto again
}
```

- If the guard does not hold, execution blocks until it does.

Producers/Consumers

Also equivalent to:

```
active proctype producer()
{
again:  if
        :: (turn == P) ->
                printf("Produce\n");
                turn = C
        :: else -> goto again
        fi;
        goto again
}
```

- `else` is only executable (true) if all other options are not executable.

Producers/Consumers

Simulation:

```
> spin prodcons.pml | more
Produce
        Consume
Produce
        Consume
Produce
        Consume
Produce
        Consume
Produce
        Consume
...
```

Producers/Consumers Extended

We can extend the example to more processes for each type:

```
active [2] proctype producer {...}
```

The alternation is no more guaranteed. Simulation:

```
> spin prodcons2_flaw.pml | more
        Produce
                        Consume
                Consume
        Produce
                        Consume
        Produce
Produce
                Consume
...
```

Producers/Consumers Extended

Reason:

```
> spin -i prodcons2_flaw.pml
Select a statement
        choice 3: proc  1 (producer) line   7 "prodcons2_flaw.pml" (state
4) [((turn==P))]
        choice 4: proc  0 (producer) line   7 "prodcons2_flaw.pml" (state
4) [((turn==P))]
Select [1-4]: 3
Select a statement
        choice 3: proc  1 (producer) line   9 "prodcons2_flaw.pml" (state
2) [printf('Produce\\n')]
        choice 4: proc  0 (producer) line   7 "prodcons2_flaw.pml" (state
4) [((turn==P))]
Select [1-4]: 4
```

Producers/Consumers Extended

A correct declaration for the producer:

```
active [2] proctype producer()
{
        do
        :: request(turn, P, N) ->
                printf("P%d\n", _pid);
                assert(who == _pid);
                release(turn, C)
        od
}
```

- `assert` aborts the program if the expression returns a zero result, otherwise it is just passed.

Producers/Consumers Extended

Definition of `request`:

```
inline request(x, y, z) {
        atomic { x == y -> x = z; who = _pid }
}
```

- **inline** functions like C macros (their body is directly pasted into the body of a proctype at each point of invocation)
- **atomic**: when it starts, the process will keep running until all steps will complete.
- The executability of the atomic sequence is determined by the first statement.

Producers/Consumers Extended

File prodcons2.pml:

```
mtype = { P, C, N };

mtype turn = P;
pid   who;

inline request(x, y, z) {
        atomic { x == y -> x = z; who = _pid }
}

inline release(x, y) {
        atomic { x = y; who = 0 }
}
...
```

Producers/Consumers Extended

Simulation:

```
> spin prodcons2.pml | more
          P1
                  C3
      P0
                  C3
          P1
                  C3
          P1
```

```
            C2
      P0
                  C3
          P1
...
```

Producers/Consumers Extended

Simulation can detect errors:

```
> spin false.pml
spin: line   1 "false.pml", Error: assertion violated
spin: text of failed assertion: assert(0)
#processes: 1
  1:    proc  0 (:init:) line   1 "false.pml" (state 1)
1 process created
```

However, simulation cannot prove that error do not exist.

Producers/Consumers Extended

To prove that the assertions cannot be violated, we generate a verifier:

```
> spin -a prodcons2.pml
> cc -o pan pan.c
> ./pan
...
Full statespace search for:
        never claim             - (none specified)
        assertion violations    +
        acceptance   cycles     - (not selected)
        invalid end states      +

State-vector 28 byte, depth reached 7, errors: 0
...
```

Producers/Consumers Extended

Back to the flawed Producers/Consumers

```
mtype = { P, C };

mtype turn = P;

int msgs;

active [2] proctype producer()
{
  do
    :: (turn == P) ->
       printf("Produce\n");
       msgs++;
       turn = C
  od
}
```

```
active [2] proctype consumer()
{
  do
    :: (turn == C) ->
       printf("Consume\n");
       msgs--;
       turn = P
  od
}


active proctype monitor() {
  assert(msgs >= 0 && msgs <= 1)
}
```

```
spin -a prodcons2_flaw.pml && gcc -o pan pan.c && ./pan spin -t -p prodcons2_flaw.pml
```

2.3 Mutual Exclusion

The Mutual Exclusion problem

General algorithm

```
active [2] proctype mutex()
{
again:
        /* trying section */

        cnt++;
        assert(cnt == 1);        /* critical section */
        cnt--;

        /* exit section */
        goto again
}
```

The Mutual Exclusion problem

First tentative

```
bit flag;
byte cnt;


active [2] proctype mutex() {
again:
  flag != 1;
```

```
  flag = 1;
  cnt++;
  assert(cnt == 1);
  cnt--;
  flag = 0;
  goto again
}
```

The Mutual Exclusion problem

Second tentative

```
bit x, y;
byte cnt;

active proctype A() {
again:
  x = 1;
  y == 0;
  cnt++;
  /* critical section */
  assert(cnt == 1);
  cnt--;
  x = 0;
  goto again
}
```

```
active proctype B() {
again:
  y = 1;
  x == 0;
  cnt++;
  /* critical section */
  assert(cnt == 1);
  cnt--;
  y = 0;
  goto again
}
```

Dekker/Dijkstra algorithm

Trying session:

```
flag[i] = true;
do
:: flag[j] ->
        if
        :: turn == j ->
                flag[i] = false;
                !(turn == j);
                flag[i] = true
        :: else -> skip
        fi
:: else ->
        break
od;
```

- `flag` indicates an intention to enter the critical section
- `turn` indicates who has priority between the two processes.

Dekker/Dijkstra algorithm

Exit session:

```
turn = j;
flag[i] = false;
```

Dekker/Dijkstra algorithm

Verification:

```
> spin -a dekker.pml
> cc -o pan pan.c
> ./pan
...
Full statespace search for:
        never claim             - (none specified)
        assertion violations    +
        acceptance   cycles     - (not selected)
        invalid end states      +

State-vector 20 byte, depth reached 67, errors: 0
...
```

Doran&Thomas change

Is the outer loop really necessary?

```
flag[i] = true;
if
:: flag[j] ->
        if
        :: turn == j ->
                flag[i] = false;
                !(turn == j);
                flag[i] = true
        :: else -> skip
        fi
:: else
fi;
```

Doran&Thomas change

Verification:

```
> spin -a doran.pml
> cc -o pan pan.c
> ./pan
...
pan: assertion violated (cnt==1) (at depth 117)
pan: wrote doran.pml.trail
...
```

`doran.pml.trail` contains a counterexample with length 117.

Doran&Thomas change

We can use a breadth-first search to find the shortest counterexample:

```
> cc -DBFS -o pan pan.c
> ./pan
...
pan: assertion violated (cnt==1) (at depth 12)
pan: wrote doran.pml.trail
...
```

Doran&Thomas change

Now, we can perform a guided simulation:

```
> spin -p -t doran.pml
  1:    proc  1 (mutex) line   8 ... [i = _pid]
  2:    proc  1 (mutex) line   9 ... [j = (1-_pid)]
  3:    proc  1 (mutex) line  11 ... [flag[i] = 1]
  4:    proc  1 (mutex) line  21 ... [else]
  5:    proc  1 (mutex) line  24 ... [cnt = (cnt+1)]
  6:    proc  0 (mutex) line   8 ... [i = _pid]
  7:    proc  0 (mutex) line   9 ... [j = (1-_pid)]
  8:    proc  0 (mutex) line  11 ... [flag[i] = 1]
  9:    proc  0 (mutex) line  13 ... [(flag[j])]
 10:    proc  0 (mutex) line  19 ... [else]
 11:    proc  0 (mutex) line  19 ... [(1)]
 12:    proc  0 (mutex) line  24 ... [cnt = (cnt+1)]
```

Peterson algorithm

A correct improvement: trying session

```
flag[i] = true;
turn = i;
!(flag[j] && turn == i) ->
```

exit session

```
flag[i] = false;
```

Verification:

```
> spin -a peterson.pml
> cc -o pan pan.c
> ./pan
...
State-vector 20 byte, depth reached 41, errors: 0
...
```

3 PROMELA overview

PROMELA

- PROMELA design is focused on process interaction at the system level
- Consequent features:
  - non-deterministic control structures,
  - primitives for process creation,
  - primitives for interprocess communication.
- Consequent lacks:
  - functions with return values,
  - expressions with side-effects,
  - data and functions pointers.

PROMELA is a language for building verification models (not a programming language)!

Types of objects

Three basic types of objects:

- processes
- data objects
- message channels

3.1 Processes

Process Initialization

- By means of **active** (instantiate an initial set of processes):

```
active [2] proctype you_run()
{
        printf("my pid is: %d\n", _pid)
}
```

- By means of **run** (creating new processes):

```
proctype you_run(byte x)
{
        printf("x = %d, pid = %d\n", x, _pid)
}
init {
        run you_run(0);
        run you_run(1)
}
```

Notes

- We cannot pass parameter values to *init* or to active processes.
- A newly created process may not start right after its initialization.
- To keep the system finite, only 256 processes can be alive in the same moment.
- A process "terminates" when it reaches the end of its code.
- A process "dies" when it has terminated and all processes instantiated later have died.
- A process may terminate without dying.

3.2 Data objects

Variable Scope

There are only two levels of scope:

- global: if it is declared outside all process declarations,
- process local: if it is declared within a process declaration.

```
init {  /* x declared in outer block */
        int x;
        {       /* y declared in inner block */
                int y;
                printf("x = %d, y = %d\n", x, y);
                x++;
                y++;
        }
        /* y remains in scope */
        printf("x = %d, y = %d\n", x, y);
}
```

Basic types

Type	Typical Range
bit	$0, 1$
bool	$false, true$
byte	0..255
chan	1..255
mtype	1..255
pid	0..255
short	-2^{15} .. $2^{15}-1$
int	-2^{31} .. $2^{31}-1$
unsigned	0 .. 2^n-1

Typical declarations

```
bit x, y;           /* two single bits, initially 0   */
bool turn = true;   /* boolean value, initially true  */
byte a[12];         /* all elements initialized to 0  */
chan m;             /* uninitialized message channel  */
mtype n;            /* uninitialized mtype variable   */
short b[4] = 89;    /* all elements initialized to 89 */
int cnt = 67;       /* integer scalar, initially 67   */
unsigned v : 5;     /* unsigned stored in 5 bits      */
unsigned w : 3 = 5; /* value range 0..7, initially 5  */
```

Data structures

```
typedef Field {
        short f = 3;
        byte  g
};
typedef Record {
        byte a[3];
        int fld1;
        Field fld2;
        chan p[3];
        bit b
};
proctype me(Field z) { z.g = 12 }
init { Record goo; Field  foo;
        run me(foo)
}
```

Arrays and Data structures

- A structure can be passed as argument to a **run** statement, provided it contains no arrays. (In the example, *foo* can be passed, *goo* cannot.)
- Multi-dimensional arrays are not supported, although there are indirect ways:

```
typedef Array {
        byte el[4]
};

Array a[4];
```

3.3 Message Channels

Message Channels

- Channels are used to transfer messages between active processes.
- They store messages in first-in first-out order.
- Two types:
  - buffered channels,
  - rendezvous ports, also called synchronous channels.

Buffered Channels

- Declaration:

  ```
  chan qname = [16] of { short, byte, bool }
  ```

  This channel can store up to 16 messages, each consisting of 3 fields of the types listed.

- A field can be a user-defined type, but not an array.
- Sending a message:

  ```
  qname!expr1,expr2,expr3
  ```

  The process blocks if the channel is full.

- Receiving a message:

  ```
  qname?var1,var2,var3
  ```

  The process blocks if the channel is empty.

Alternative

- The first message field is a message type indication:

  ```
  qname!expr1(expr2,expr3)
  qname?var1(var2,var3)
  ```

- Some parameters can be given as constants:

  ```
  qname?cons1,var2,cons2
  ```

  The process blocks if the channel is empty and if the sent values do not match the constants.

- The built-in function `len` can be used to get the number of messages in a given channel:

  ```
  len(qname)
  ```

Rendezvous Ports

- Declaration of a rendezvous port: it can pass single byte messages

  ```
  chan port = [0] of { byte }
  ```

- The channel size is zero: the channel port can pass, but can not store messages.
- Message interaction is synchronous: two processes execute a send and a receive statement at the same time.

```
mtype = { msgtype };
chan name = [0] of { mtype, byte };
active proctype A()
{       name!msgtype(124);
        name!msgtype(121)
}
active proctype B()
{       byte state;
        name?msgtype(state)
}
```

Channels of channels

- Message parameters are always passed by value.
- We can pass the value of a channel from a process to another.

```
mtype = { msgtype };
chan glob = [0] of { chan };
active proctype A()
{       chan loc = [0] of { mtype, byte };
        glob!loc;
        loc?msgtype(121)
}
active proctype B()
{       chan who;
        glob?who;
        who!msgtype(121)
}
```

3.4 Executability

Statements

- Every statement is either *executable* or *blocked*.

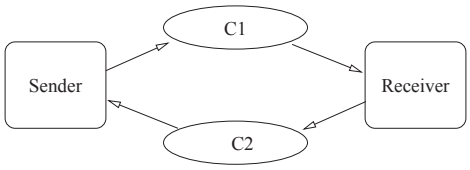
- Three main types of statements:
  - print statements
  - assignments
  - expression statements
- Print statements and assignments are always executable.
- Expression statements are executable iff they evaluate to true.
- Expressions must be side effect free.
- Exception: the `run` statement can be considered as a blocking expression:
  - it blocks when there are 256 processes alive;
  - if it does not block, it creats a new process.

4 Asynchronous Network Problems

4.1 Reliable FIFO Communication

Reliable FIFO Communication Problem

- We want to implement a reliable FIFO communication using less reliable channels.
- A user *Sender* sends messages to another user *Receiver* by means of two channels C_1 and C_2
- C_1 and C_2 are non-reliable channels.
- The non-reliable channels may lose or duplicate the messages.



Alternating Bit Protocol

- *Sender* tags the messages with an alternating bit (e.g. it sends `(0, msg1)`, `(1, msg2)`, `(0, msg3)`, ...).
- *Sender* repeatedly sends a message with its tag until it receives a bit acknowledgment from *Receiver*.

- Suppose *Sender* has sent `(tag, msg)` and receives `b` as acknowledgment. If `b` is equal to `tag`, then it means that *Receiver* has received the right message, so it obtains a new message and tags it with a different value; otherwise it sends `(tag, msg)` again.
- Similarly, suppose *Receiver* receives `(tag, msg)`. If `tag` is different from the last received bit, then it means that it is a new message; otherwise, the message is old. In both cases, *Receiver* sends `tag` back to *Sender* to communicate the correct receipt of the message.

Alternating Bit Protocol

```
mtype = { msg, ack };

chan to_sndr = [2] of { mtype, bit };
chan to_rcvr = [2] of { mtype, bit};

active proctype Sender()
{
...
}

active proctype Receiver()
{
...
}
```

Alternating Bit Protocol

```
active proctype Sender()
{
  bit seq_out, seq_in;

  /* obtain first message */
  do
    :: to_rcvr!msg(seq_out) ->
       to_sndr?ack(seq_in);
       if
         :: seq_in == seq_out ->
            /* obtain new message */
            seq_out = 1 - seq_out;
         :: else
       fi
  od
}
```

Alternating Bit Protocol

```
active proctype Receiver()
{
  bit seq_in;
  do
    :: to_rcvr?msg(seq_in)
    :: to_sndr!ack(seq_in)
  od
}
```

Example of simulation

- Receiver sends 2 ack (then it is blocked)
- Sender sends one message
- two possibilities:
  - Receiver receives the message
  - Sender receives one ack

Exercise

- Try with:

```
active proctype Receiver()
{       bit seq_in, last_seq_in;
        int received;
        do
        :: to_rcvr?msg(seq_in, received) ->
           if
             :: (seq_in != last_seq_in) ->
                printf("Received: %d\n", received);
                last_seq_in = seq_in
             :: else
           fi;
           to_sndr!ack(seq_in)
        od
}
```

4.2 Leader Election

Leader Election Problem

- N processes are the nodes of a unidirectional ring network: each process can send messages to its clockwise neighbor and receive messages from its counterclockwise neighbor.