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DPHPC: SPIN Tutorial

Recitation session

Credits: *http://spinroot.com/spin/Doc/SpinTutorial.pdf*

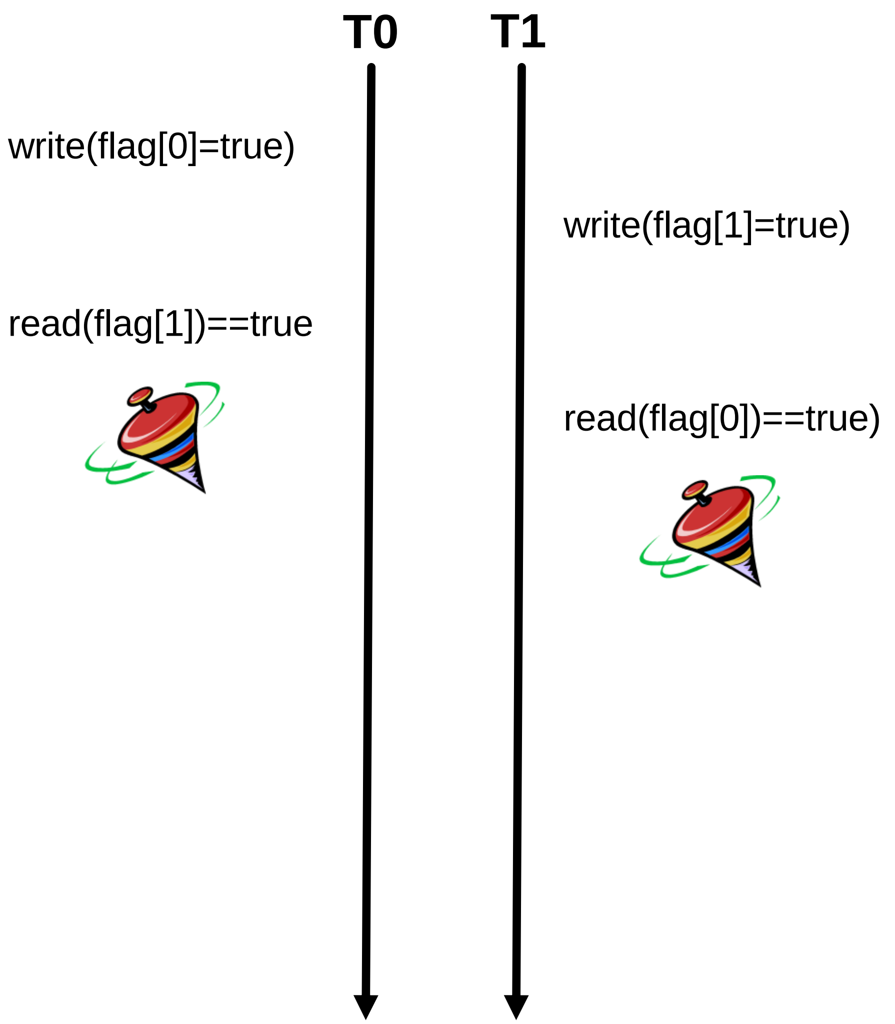
Systems@ETH zürich

2-threads: LockOne

```
volatile int flag[2];

void lock() {
  int j = 1 - tid;
  flag[tid] = true;
  while (flag[j]) {} // wait
}

void unlock() {
  flag[tid] = false;
}
```

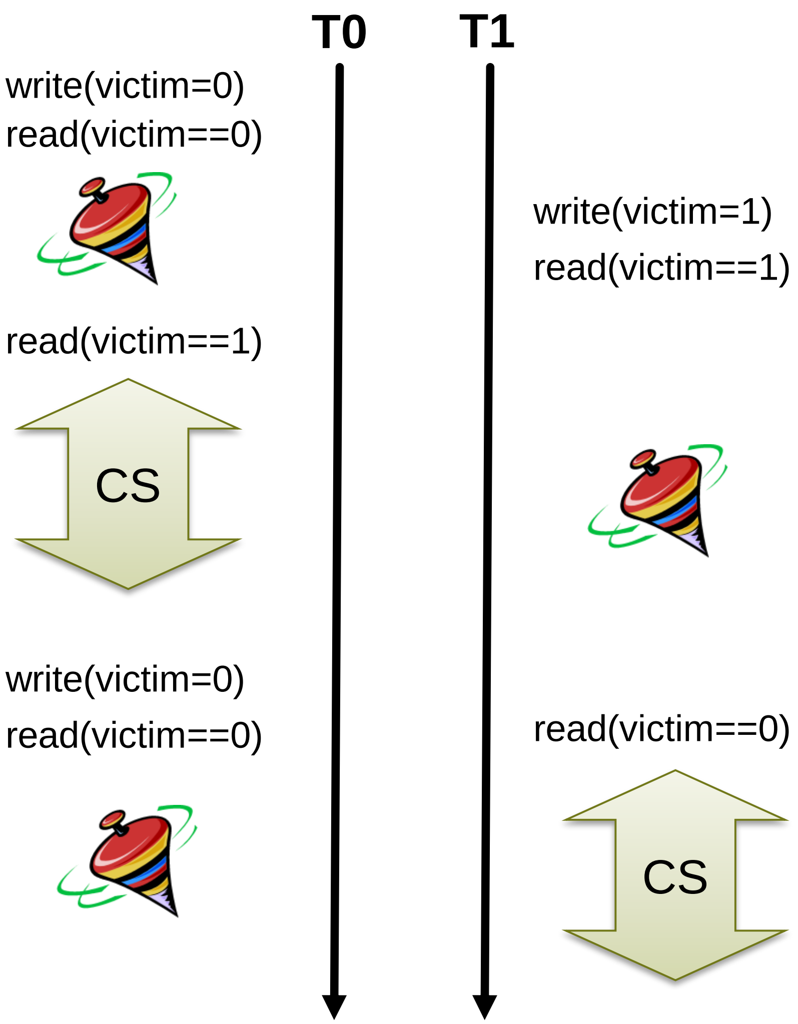


2-threads: LockTwo

```
volatile int victim;

void lock() {
  victim = tid; // grant access
  while (victim == tid) {} // wait
}

void unlock() {}
```



2-threads: Peterson lock

```
volatile int flag[2];
volatile int victim;

void lock() {
  int j = 1 - tid;
  flag[tid] = 1;      // I'm interested
  victim = tid;       // other goes first
  while (flag[j] && victim == tid) {}; // wait
}

void unlock() {
  flag[tid] = 0;  // I'm not interested
}
```

Locks

MCS Lock

```
typedef struct qnode {
  struct qnode *next;
  int succ_blocked;
} qnode;

qnode *lck = NULL;

void lock(qnode *lck, qnode *qn) {
            = NULL;
           red = FetchAndSet(lck, qn);
            NULL) {
    qn->locked = 1;
    pred->next = q
    while(qn->lock
} }

void unlock(qnode * lck, qnode *qn) {

  }
  qn->next->locked = 0; // free next waiter
  qn->next = NULL;
}
```

TATAS

bo
b

Complicated

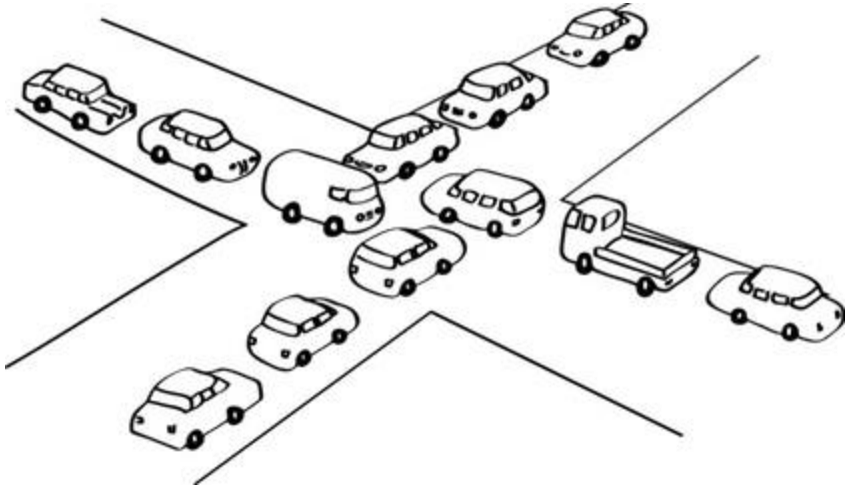
Difficult to optmize

Over-optimization can quickly lead to incorrect locks

How can make sure locks (or other distributed algorithms) are correct in practice?

How to check correctness?

- **Common design flaws in designing distributed systems:**
  - **Deadlock**
  - **Livelock**, starvation
  - **Underspecification**
    Unexpected messages
  - **Overspecification**
    Dead code
  - **Constraint violations**
    Buffer overruns
    Array bound violations



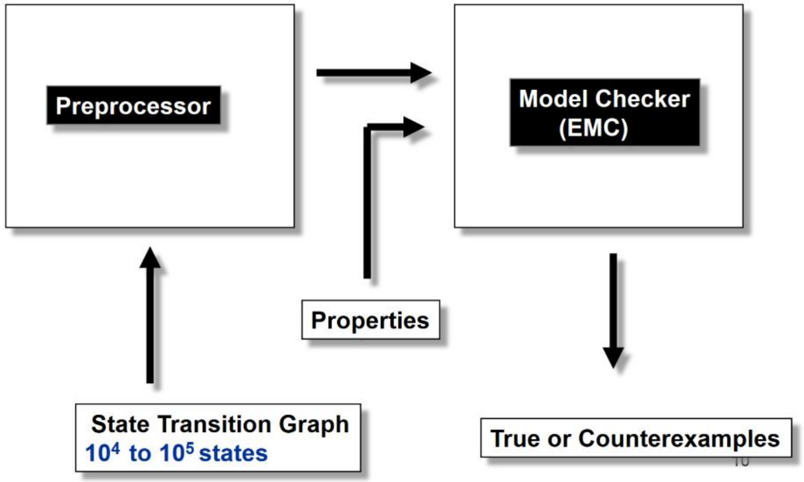
Model checking

- **Model checking verifies a program by using software to analyze its state space**

- **Alternative: mathematical deductive methods**
  - Constructing a proof requires mathematical insights and tenacity
  - The complexity depends on the algorithms itself

- **Deductive proofs are more elegant and pow**

State: IP + 2 register (regP, regQ) + global var n
IP: 4 value (1…4) – one per process
Registers + n: 3 values (0, 1, 2)
4x4x3x3x3=432




```
integer n=0

process P                               process Q
        integer regP=0                          integer regQ=0
p1:     load n into regP                p1:     load n into regQ
p2:     increment regP                  p2:     increment regQ
p3:     store regP into n               p3:     store regQ into n
p4:     end                             p4:     end
```

How many states?

Ben-Ari, Mordechai Moti. "A primer on model checking." *ACM Inroads 1.1 (2010): 40-47.*

Space Explosion Problem

- **The system is described as a State Transition Graph**
- **We have a combinatorial explosion of systems states**

- **How to handle it?**

- **Increase the abstraction**

- **Not all the states are actually reachable**
  - Generate the states on the fly: only the ones that can be reached are generated

- **Avoid to visit the same state multiple times**
  - E.g., keep a hash table to index the visited states

SPIN – Introduction

- ***SPIN:*** **Simple Promela Interpeter**
  - Goal: analyze the logical consistency of concurrent systems
  - Concurrent systems are described in the modelling language called **Promela**

- ***Promela:*** **Protocol/Process Meta Language**
  - **Allows dynamic creation of concurrent processes**
  - **Communication via message passing can be**
    Synchronous (aka rendezvous)
    Asynchronous (aka buffered)
  - **C-like language**
  - **Enables you to model a finite-state system**

- **Warning:** If that description is "too far off" from our code, we risk specifying the wrong state machine!

Promela Model

Promela model consist of:

- Type declarations
- Channel declarations
- Variable declarations
- Process declarations
- [init process]

```
mtype = {MSG, ACK};
chan toS = ...
chan toR = ...
bool flag;

proctype Sender() {
   ...
}

proctype Receiver() {
   ...
}

init {
   ...
}
```

process body

creates processes

name

formal parameters

```
proctype Sender(chan in; chan out) {
    bit sndB, rcvB;
    do
    :: out ! MSG, sndB ->
          in ? ACK, rcvB;
          if
          :: sndB == rcvB -> sndB = 1-sndB
          :: else -> skip
          fi
    od
}
```

local variables

body

The body consist of a sequence of statements.

A **process type** (`proctype`) consist of

- a name
- a list of formal parameters
- local variable declarations
- body

Promela - Processes

- **Identified by the proctype keyword**
- **Can be executed concurrently**
- **You can create multiple processes of the same type**

- **Each process has its own local state defined by:**
  - Program counter
  - Local variables

- **Communication between processes:**
  - Shared variables
  - Channels

- **Processes can be created using the run keyword**
  - It returns the pid of the created process
  - Can be called at any point

name
formal parameters

```
proctype Sender(chan in; chan out) {
    bit sndB, rcvB;
    do
    :: out ! MSG, sndB ->
           in ? ACK, rcvB;
           if
           :: sndB == rcvB -> sndB = 1-sndB
           :: else -> skip
           fi
    od
}
```

local variables
body

The body consist of a sequence of statements.

Promela: Hello World

```
active proctype Hello() {
    printf("Hello process, my pid is: %d\n", _pid);
}

init{
    int lastpid;
    printf("init process, my pid is: %d\n", _pid);
    lastpid = run Hello();
    printf("last pid was: %d\n", lastpid);
}
```

random seed

```
$ spin -n2 hello.pr
init process, my pid is: 1
        last pid was: 2
Hello process, my pid is: 0
                Hello process, my pid is: 2
3 processes created
```

running SPIN in random simulation mode

Promela: Variables and Types

- **Types: 5 basic types**
  - `bit, bool, byte, short, int`
- **Arrays**
  - `byte a[27];`
- **Records (structs)**
  - ```
    typedef Record{
      short f1;
      byte f2;
    }
    Record rr;
    rr.f1 = …
    ```
- **Global and local variables are initialized to 0 by default**

```
int ii;
bit bb;

bb=1;
ii=2;

short s=-1;

typedef Foo {
  bit bb;
  int ii;
};
Foo f;
f.bb = 0;
f.ii = -2;

ii*s+27 == 23;
printf("value: %d", s*s);
```

assignment =

declaration + initialisation

equal test ==
```

Promela: Statements

- **The body of a process consists of a sequence of statements.**
  - Executable: the statement can be executed immediately
  - Blocked: it cannot be executed

- **Assignments are always executable**

- **An expression is executable only if it evaluates to non-zero**
  - **`2 < 3`** always executable
  - **`x < 27`** executable only if `x < 27`
  - **`3 + x`** executable only if `x != -3`

- **The assert(<expr>) statement is always executable**
  - SPIN exits with an error if an assert evaluates to 0
  - Used to check if properties hold

```
int x;
proctype Aap()
{
  int y=1;
  skip;
  run Noot();
  x=2;
  x>2 && y==1;
  skip;
}
```

Executable if Noot can be created…

Can only become executable if a some other process makes x greater than 2.

Semantic

- **Pamela processes are executed concurrently and scheduled in a non-deterministic fashion**
- **Execution of statements of different processes is interleaved**
  - All statements are atomic
- **Each process may have multiple actions ready to be executed**
  - Only one is non-deterministically chosen to be executed

Promela: Mutual Exclusion? (1)

```
bit flag;          /* signal entering/leaving the section */
byte mutex;       /* # procs in the critical section. */

proctype P(int i) {
       flag != 1;
       flag = 1;
       mutex++;
       printf("MSC: P(%d) has entered section.\n", i);
       mutex--;
       flag = 0;
}

proctype monitor() {
       assert(mutex != 2);
}

init { run P(0); run P(1); run monitor(); }
```

Both processes can pass the flag!=1
"at the same time"

Promela: Mutual Exclusion? (2)

```
bit x, y;          /* signal entering/leaving the section */
byte mutex;  /* # of procs in the critical section. */

active proctype A() {
        x = 1;
        y == 0;
        mutex++; mutex--;
        x = 0;
}

active proctype B() {
        y = 1;
        x == 0;
        mutex++; mutex--;
        y = 0;
}

active proctype monitor() {
        assert(mutex != 2);
}
```

Both processes can pass execute x=1 and y=1 “at the same time”...

PROMELA Semantics: if

```
if
:: choice_1 -> stat1.1; stat1.2; stat1.3; …
:: choice_2 -> stat2.1; stat2.2; stat2.3; …
:: …
:: choice_n -> statn.1; statn.2; statn.3; …
:: else     -> skip
fi;
```

- If there is at least one choice (guard) executable, the if statement is executable and SPIN non-deterministically chooses one of the executable choices.
- The “else” choice is executable iff no other choices are
- If no choice is executable, the if-statement is blocked

PROMELA Semantics: do

```
do
:: choice1 -> stat1.
:: choice2 -> stat2.
:: …
:: choicen -> statn.
od;
```

```
mtype = { RED, YELLOW, GREEN } ;

active proctype TrafficLight() {
    byte state = GREEN;
    do
    ::  (state == GREEN)  -> state = YELLOW;
    ::  (state == YELLOW) -> state = RED;
    ::  (state == RED)    -> state = GREEN;
    od;
}
```

if- and do-statements are ordinary Promela statements; so they can be nested.

mtype (message type) models enumerations in Promela

Note: this do-loop does not contain any non-deterministic choice.

- With respect to the choices, a do-statement behaves in the same way as an if-statement
- However, instead of ending the statement at the end of the chosen list of statements, a do-statement repeats the choice selection
- The (always executable) break statement exits a do-loop statement and transfers control to the end of the loop

PROMELA Semantics: Communication

- **Communication between processes is via typed channels**

```
chan <name> = [<dim>] of {<t1>,<t2>,…,<tn>};
```

- **A channel can be synchronous (dim=0) or asynchronous (dim>0)**
  - In the first case, synchronization is needed
  - In the second, the channels act like a FIFO-buffer

Example:

```
mtype  = {MSG, ACK};
chan toS = [2] of {mtype, bit};
```

PROMELA Semantics: Communication

- **Communication between processes is via typed channels**

```
chan <name> = [<dim>] of {<t1>,<t2>,…,<tn>};
```

- **Sending:**
  - `ch ! <expr1>, <expr2>, …, <exprn>;`

    The values of `<expri>` must match the types of the channel declaration

    A send statement is executable if the channel is not full

Rendezvous communication (dim==0):
A send ch! is executable only if there is a corresponding receive ch? that can be executed simultaneously

- **Receiving**
  - `ch ? <var1>, <var2>, …, <varn>;`

    If the channel is not empty, the message is fetched from the channel
  - `ch ? <const1>, <const2>, …, <constn>;`

    Message Matching

    If the channel is not empty and the message at the front of the channel evaluates to the individual <consti>, the statement is executable and the message is removed from the channel

<vars> and <consts> can be mixed

Using spin

- **Random simulation mode: debugging/testing. Randomly resolves non-determinism**

```
spin -n<SEED> model.pr #fix the seed to reproduce scenarios
```

- **Guided simulation mode (-i): non-determinism solved by the user**

- **Verification mode: analyze all the reachable states**

```
spin -a model.pr
gcc -O2 -o pan pan.c
./pan #generates trail file if things go wrong
spin -t -p model.pr
```

Generates a verifier in C code, so that compiler can optimize it, then exhaustively searches all possible states. It can still be slow/eat all your memory.

Assignment

Hippie problem:
4 Hippies want to cross a bridge. The bridge is fragile, it can only crossed by <= 2 people at a time with a torchlight. The hippies have one torchlight and want to reach the other side within one hour. Due to different degrees of intoxication they require different amounts of time to cross the bridge: 5, 10, 20 and 25 minutes. If a pair crosses the bridge, they can only move at the speed of the slower partner.