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DPHPC: Locks, SPIN Tutorial
Recitation session

New TA

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Research areas:
- performance modelling (Extra-P)
- large-scale code analysis
- serverless architectures (AWS Lambda, Azure Functions)

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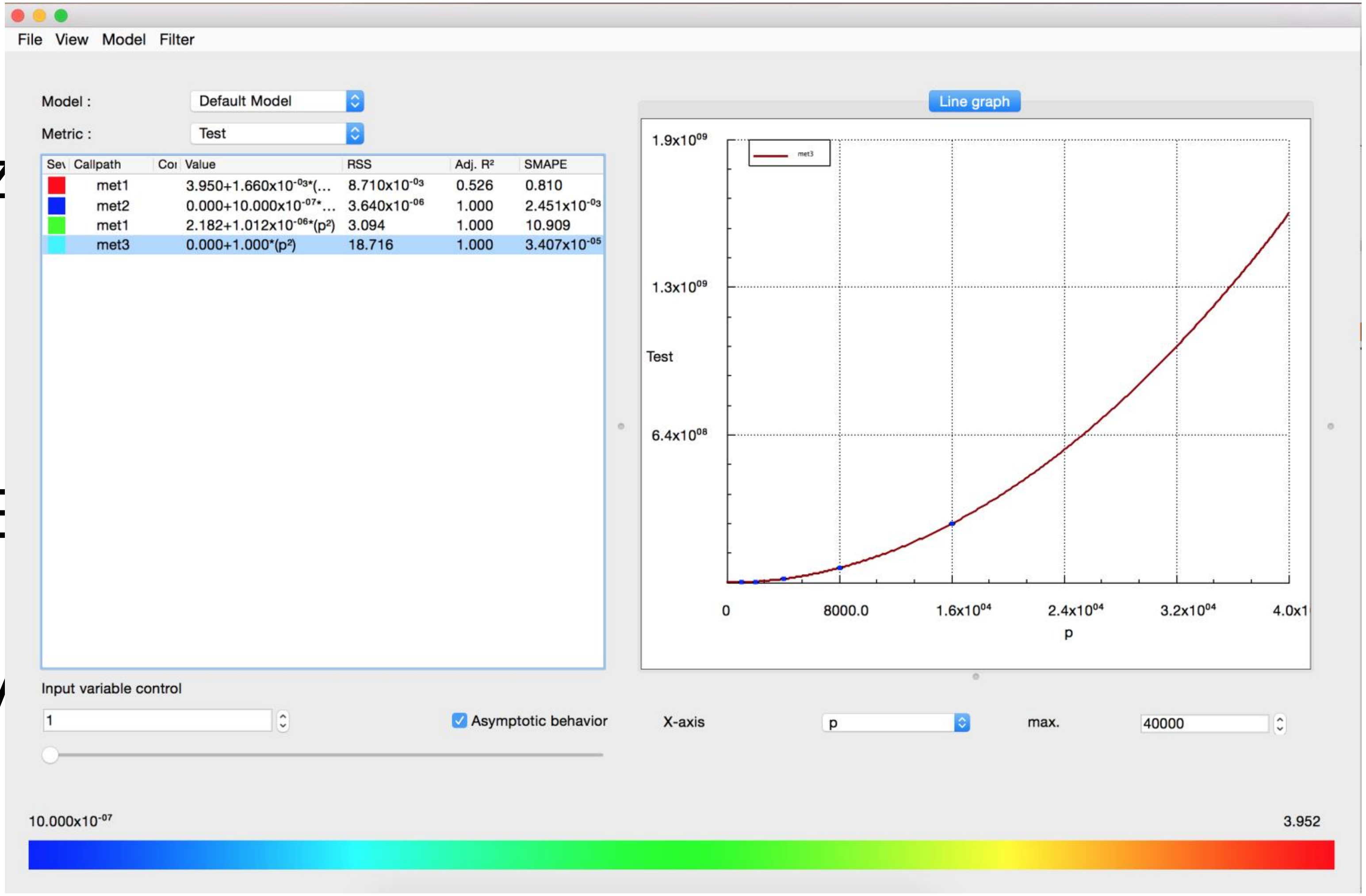

2-threads: LockOne

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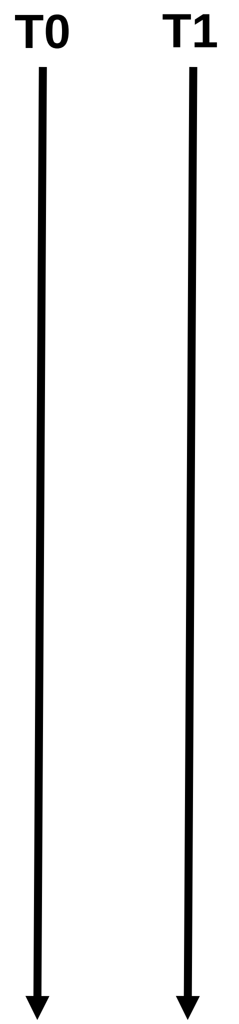

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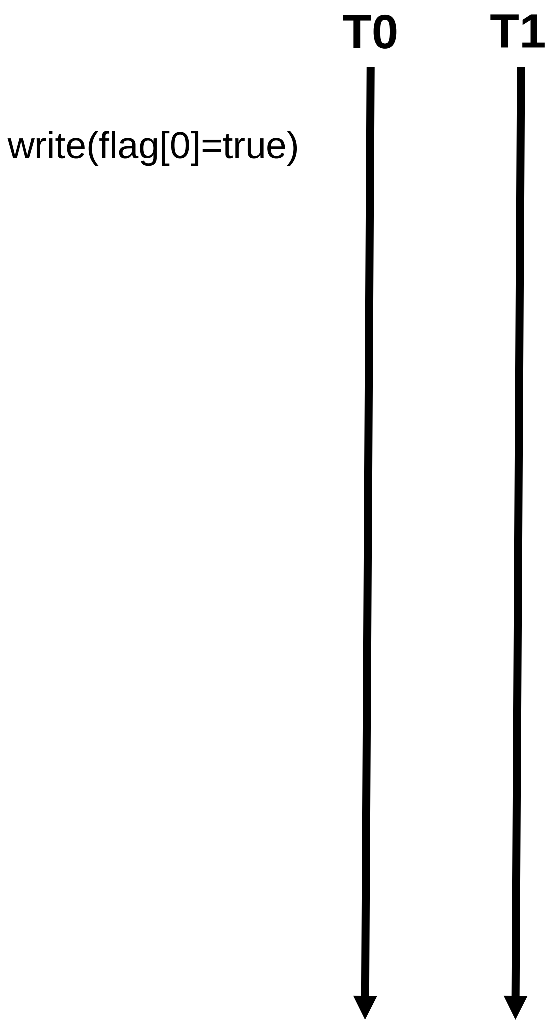

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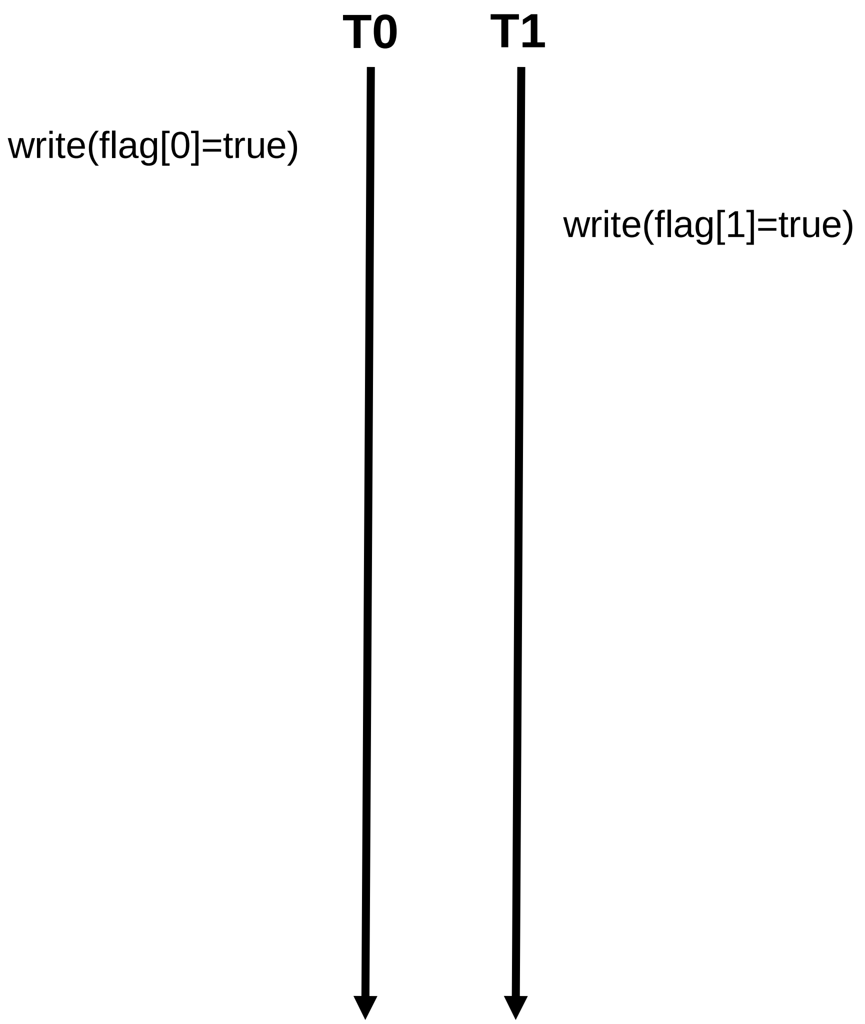

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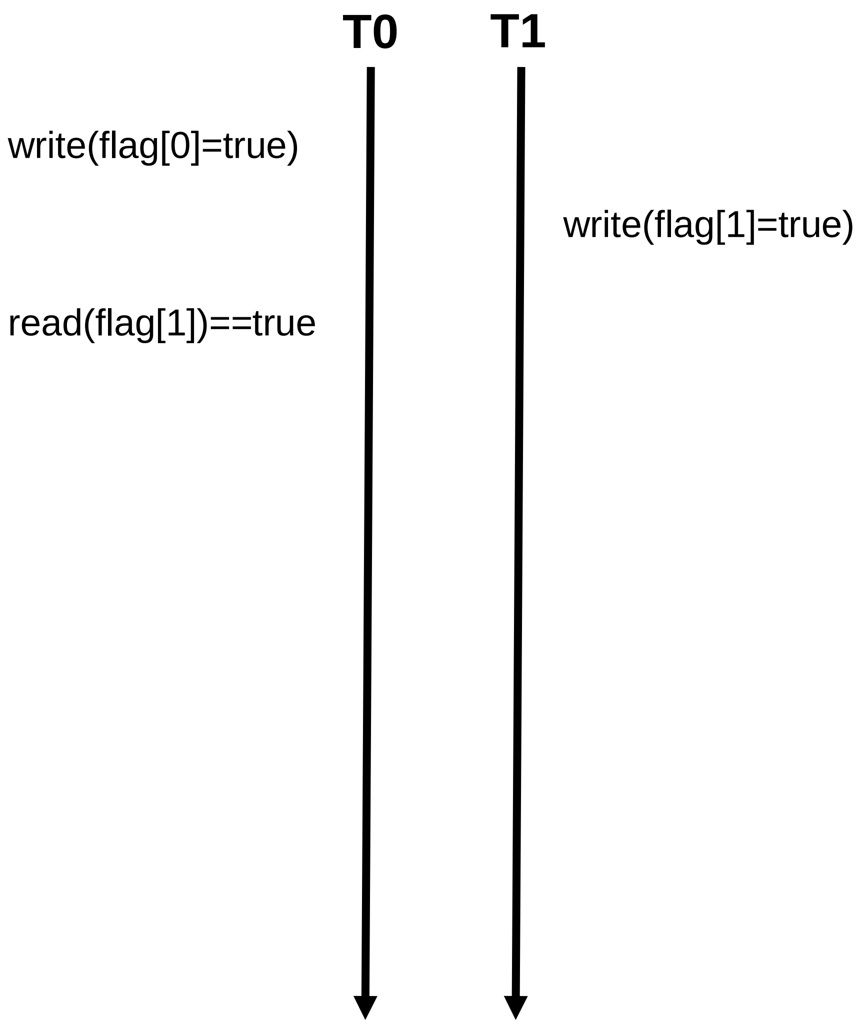

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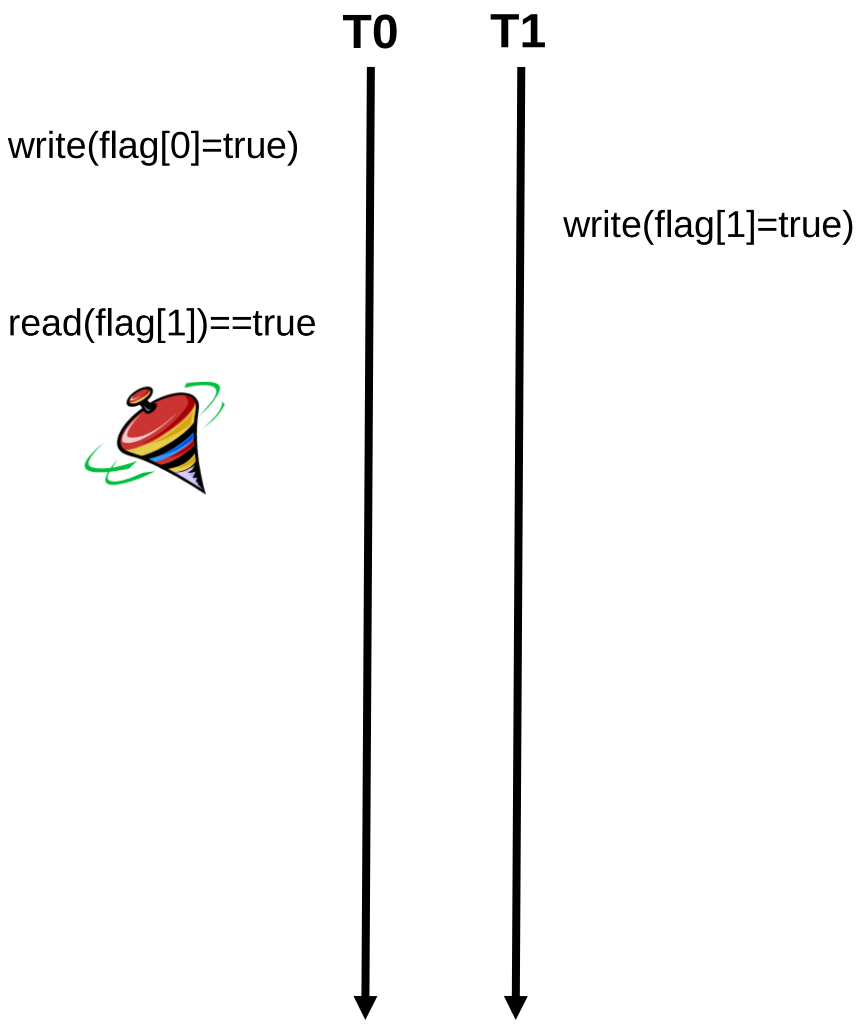

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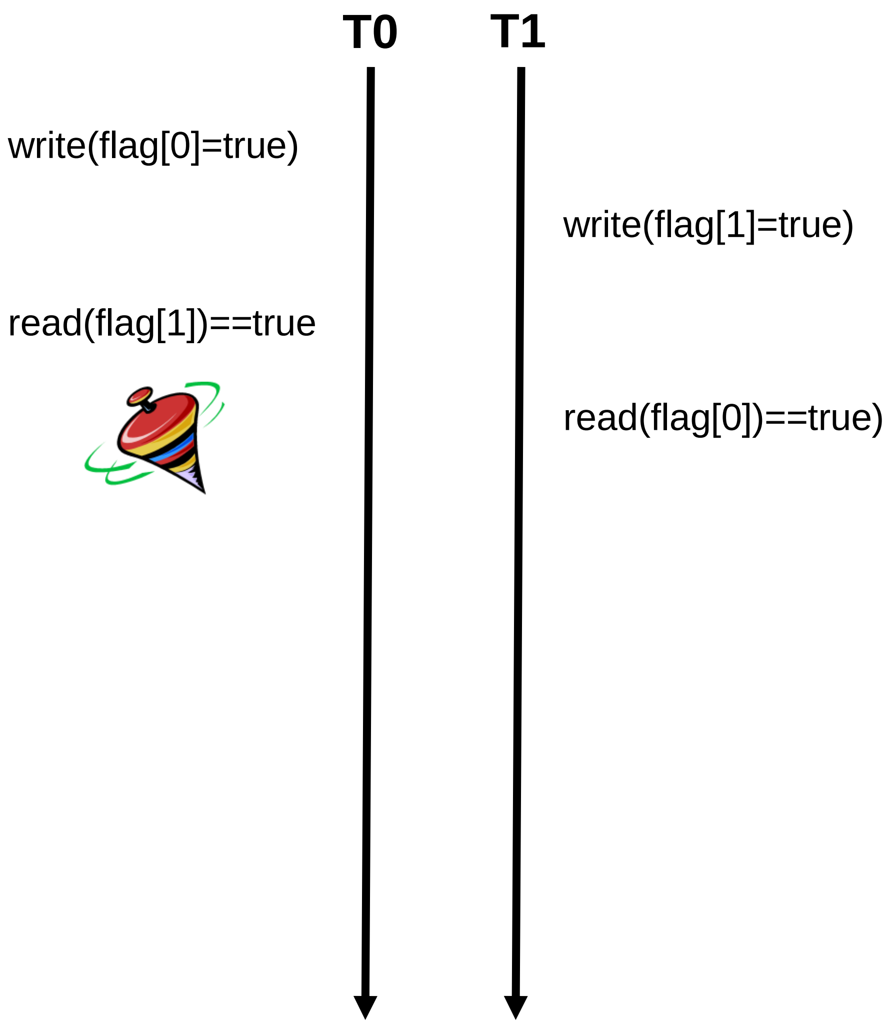

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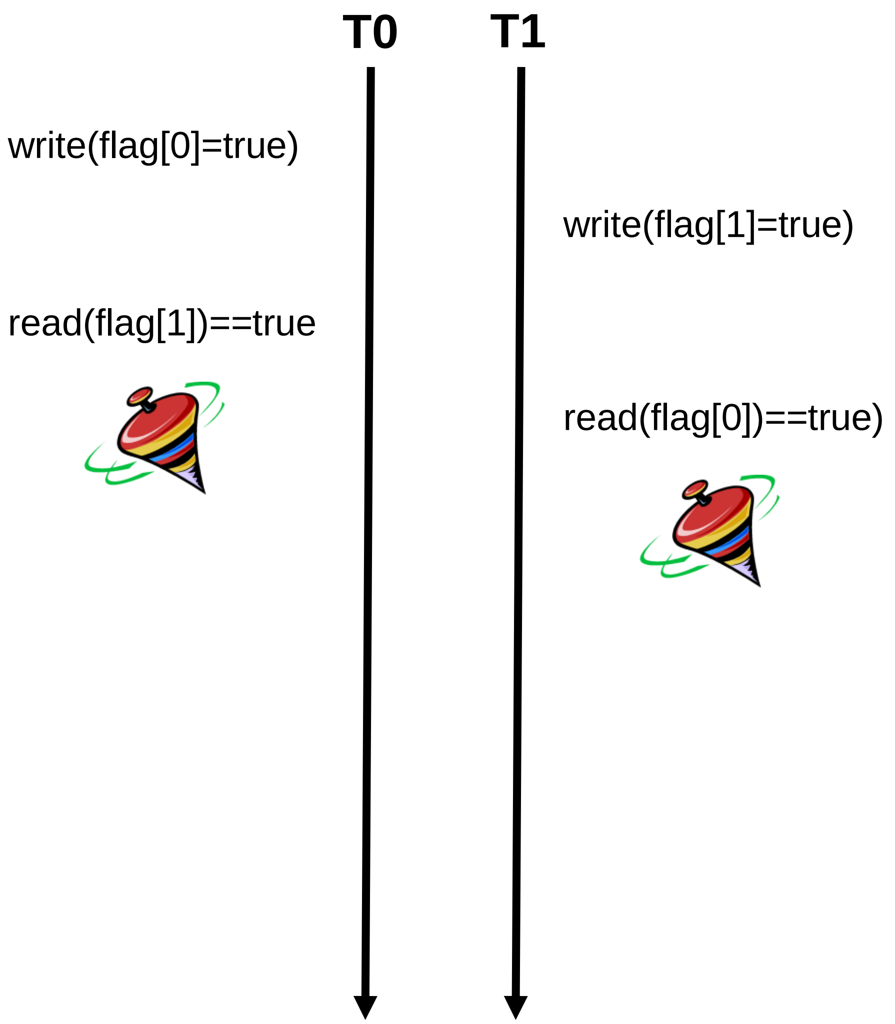

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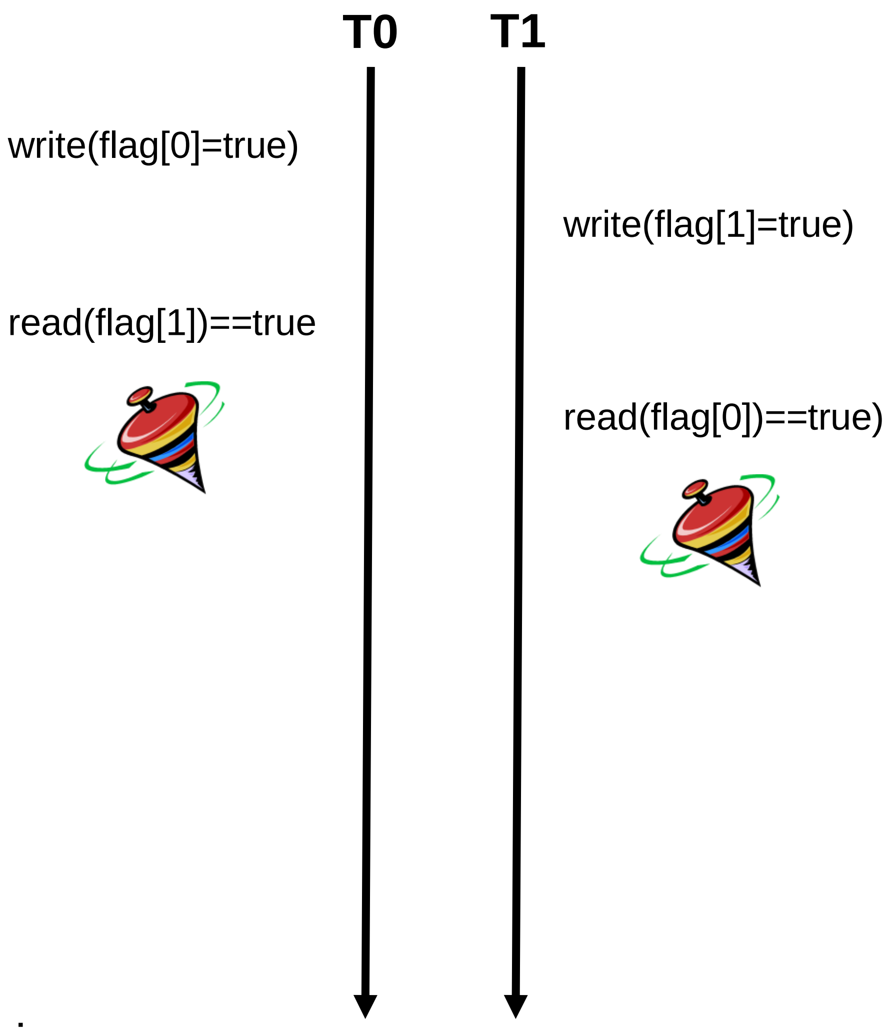
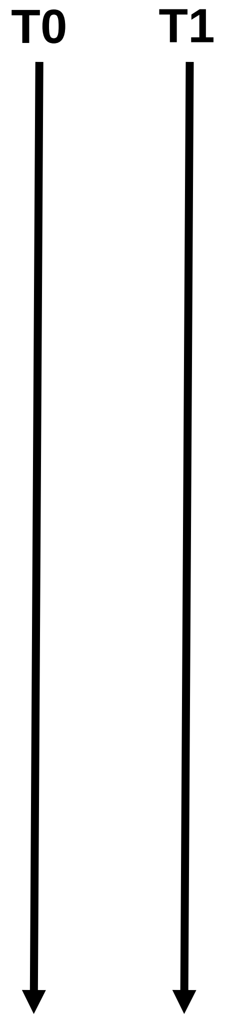


Deadlock – lock acquisition and entering CS are **not** atomic.

2-threads: LockTwo




```
volatile int victim;

void lock() {
  victim = tid; // grant access
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```
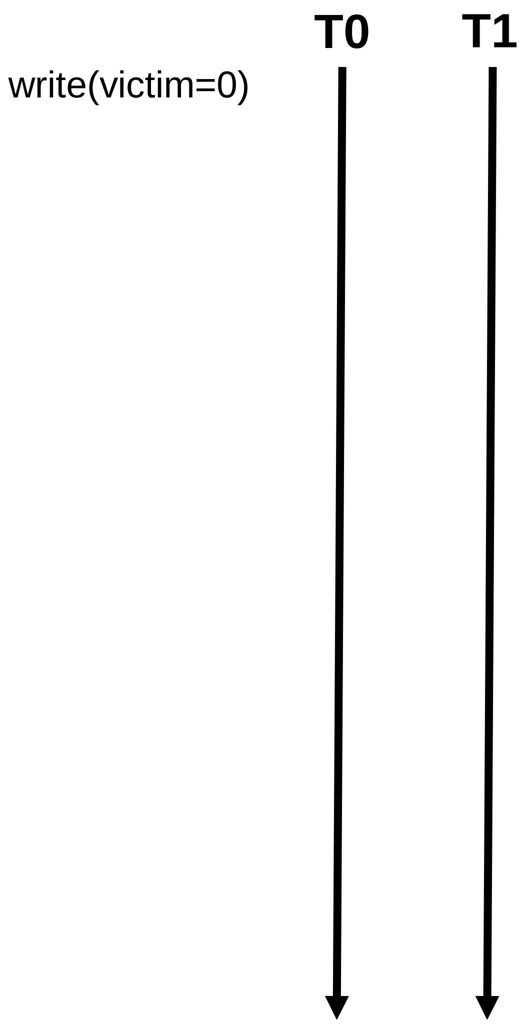

2-threads: LockTwo

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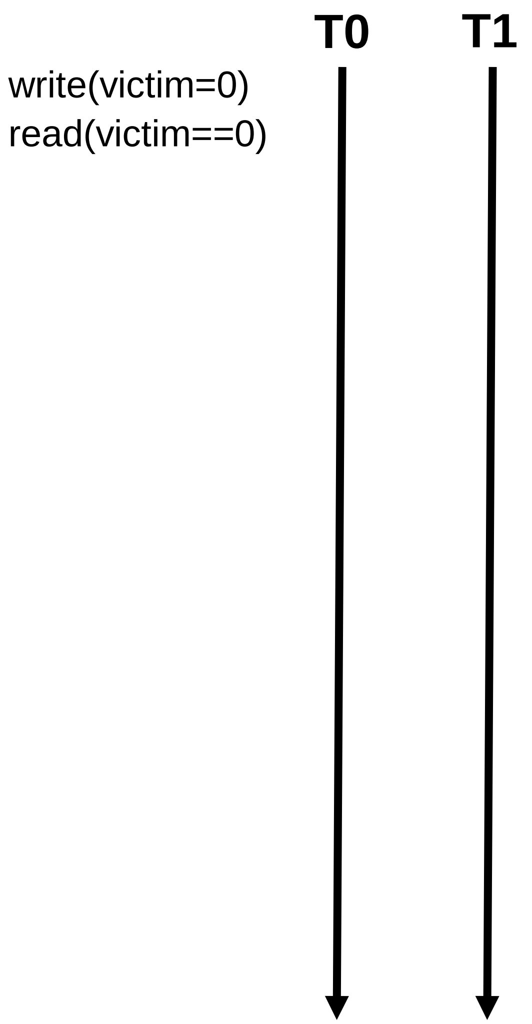


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2-threads: LockTwo

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volatile int victim;

void lock() {
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void unlock() {}
```

write(victim=0)
read(victim==0)

T0 T1

2-threads: LockTwo

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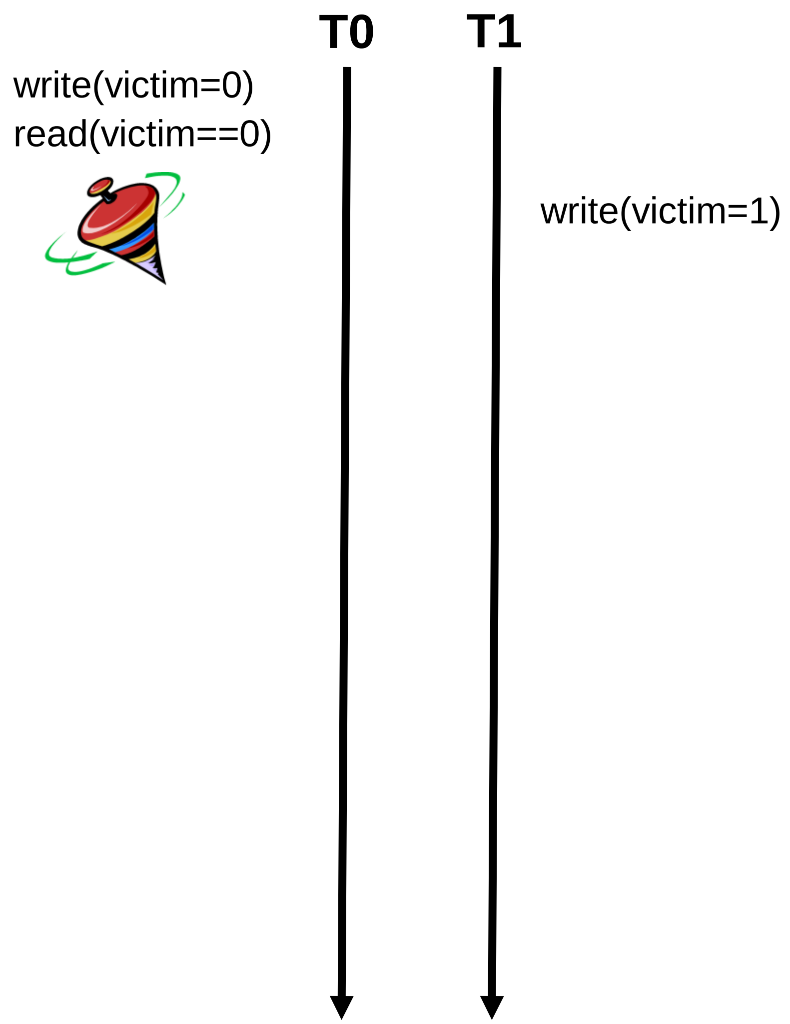

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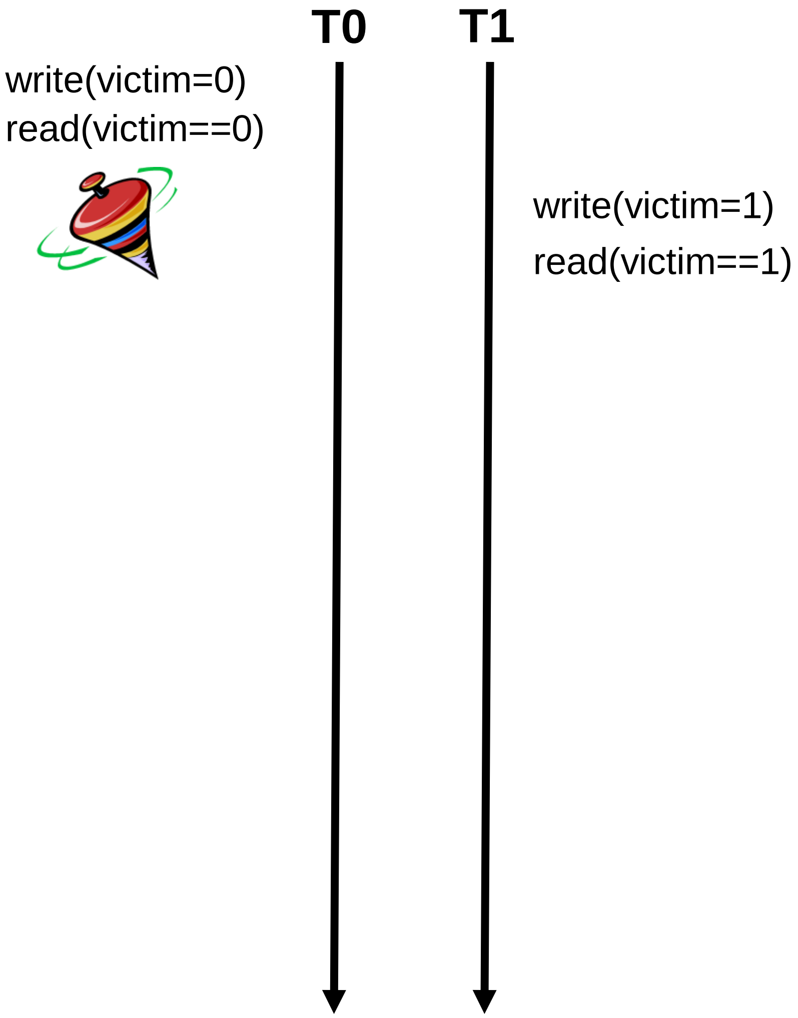

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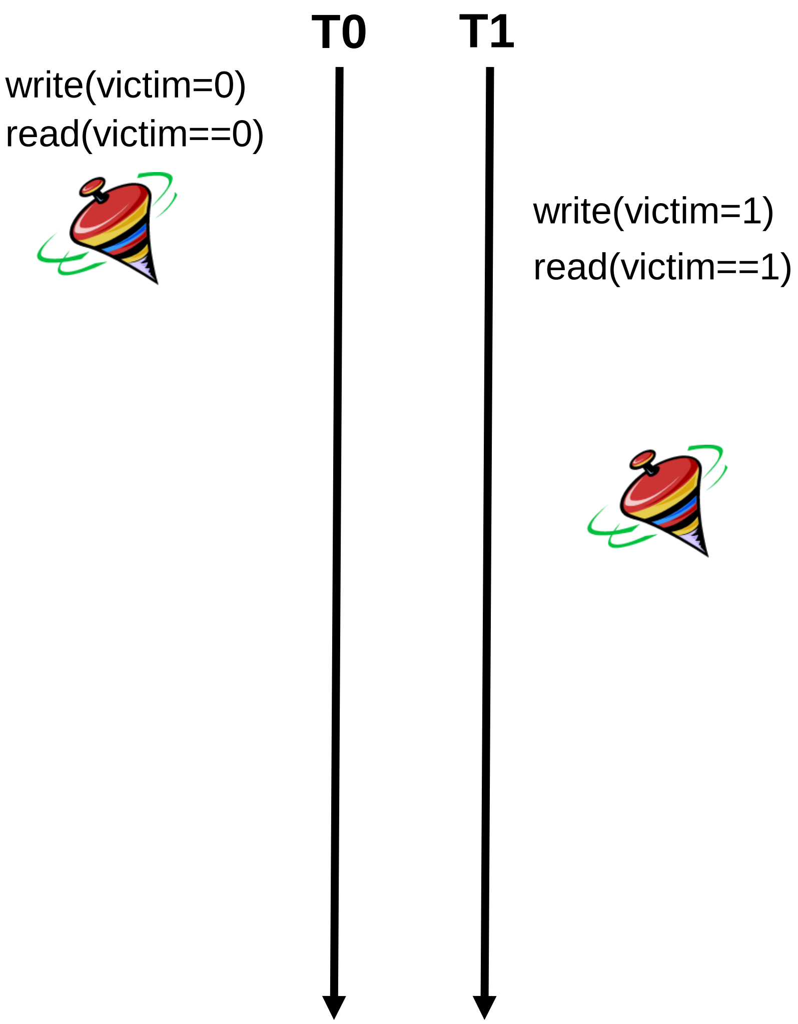

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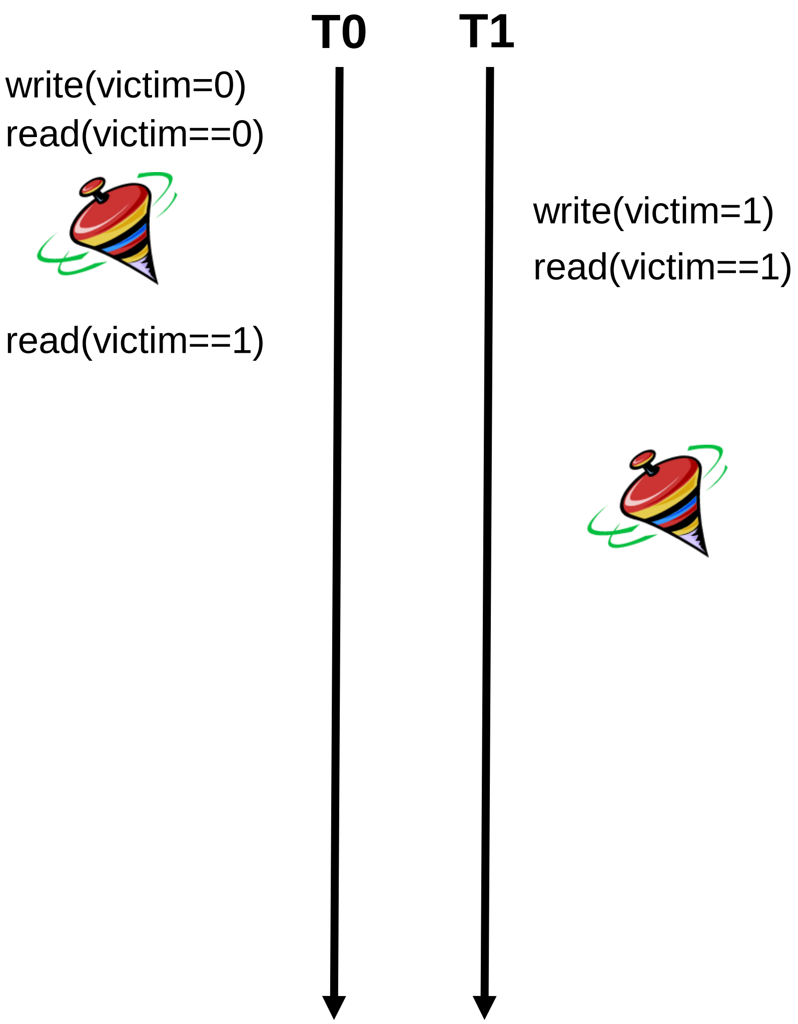

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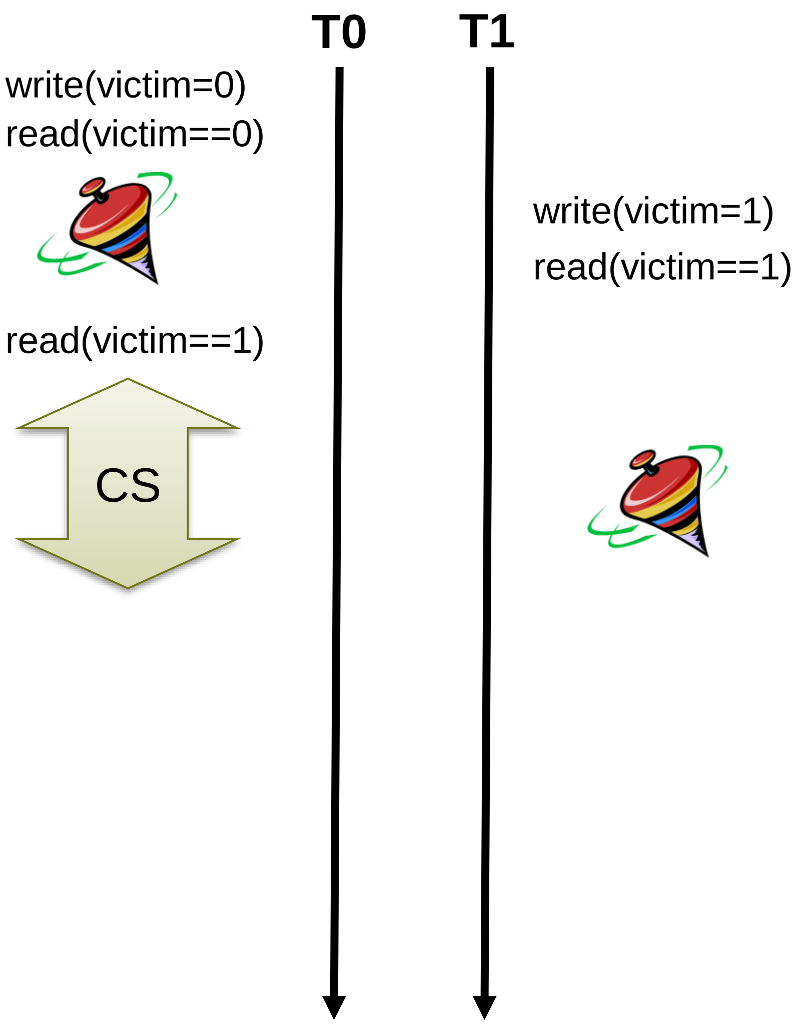

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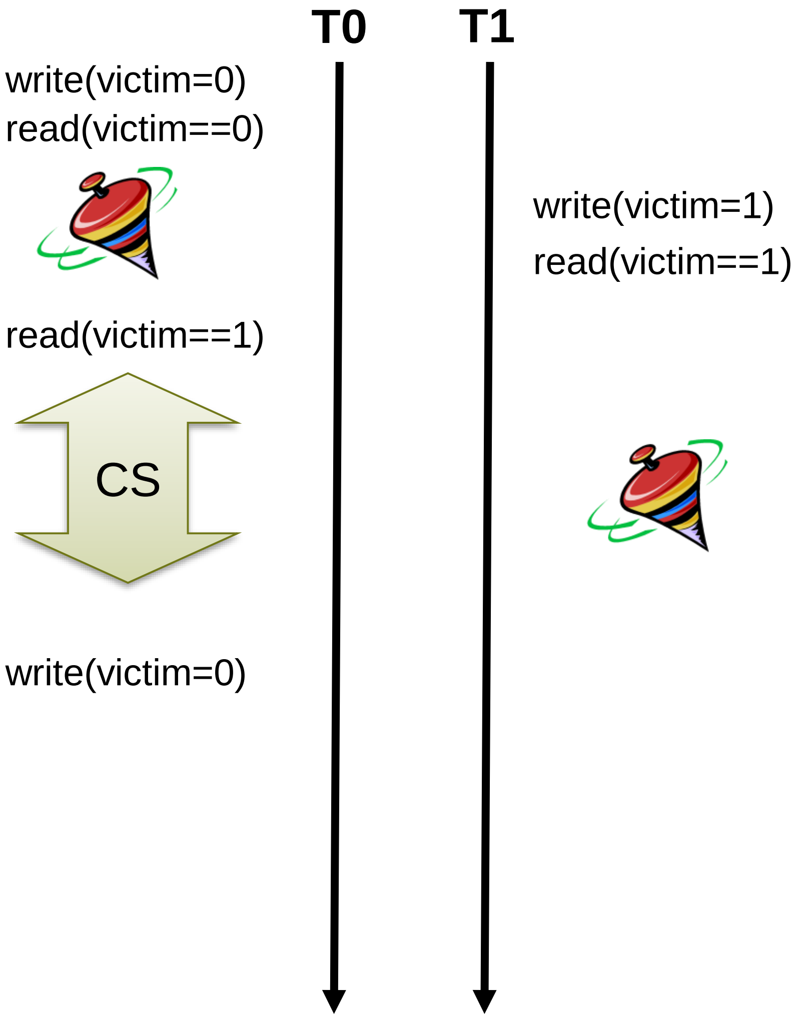

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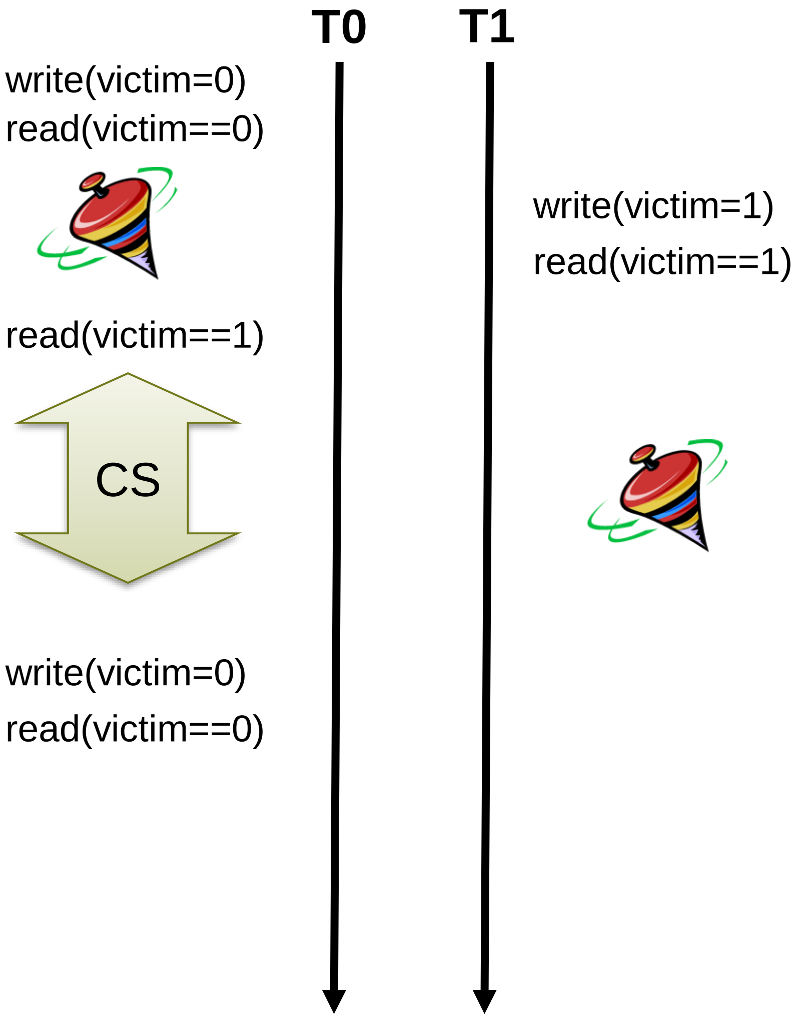

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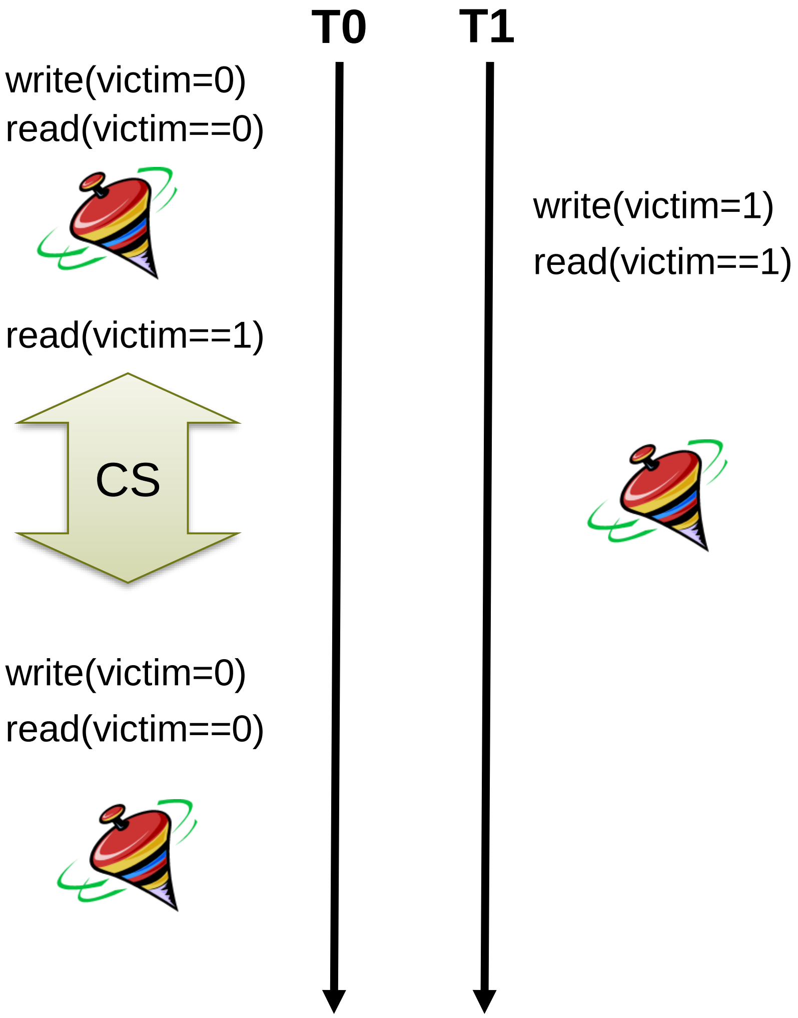

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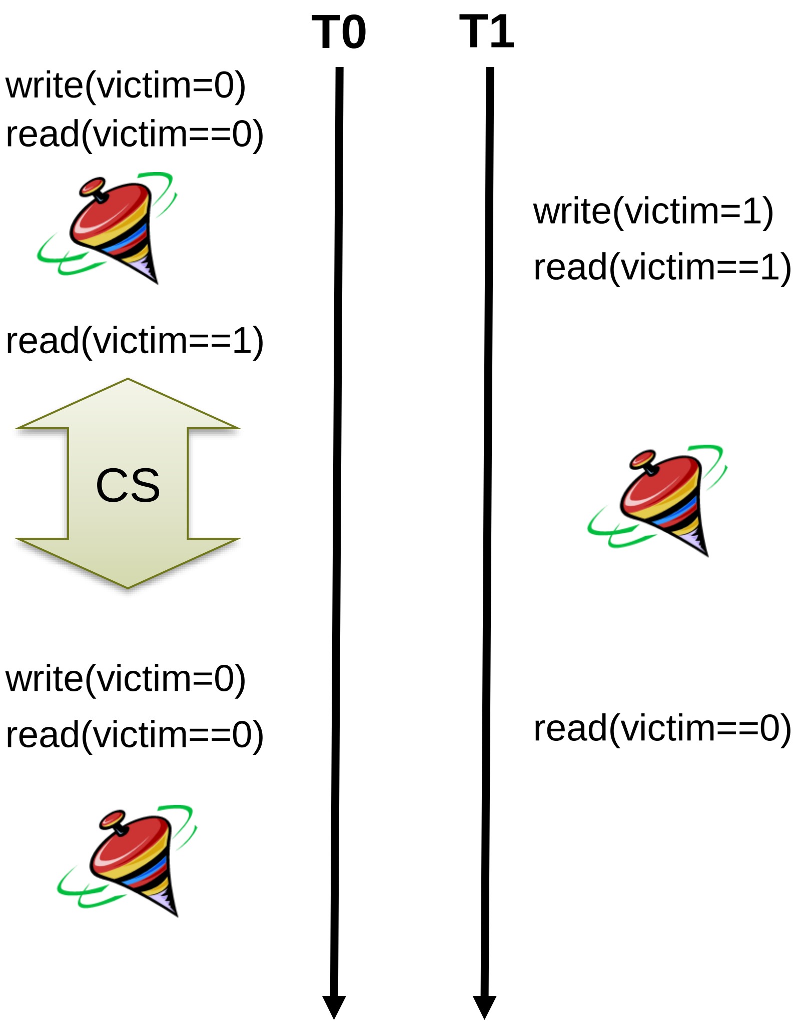

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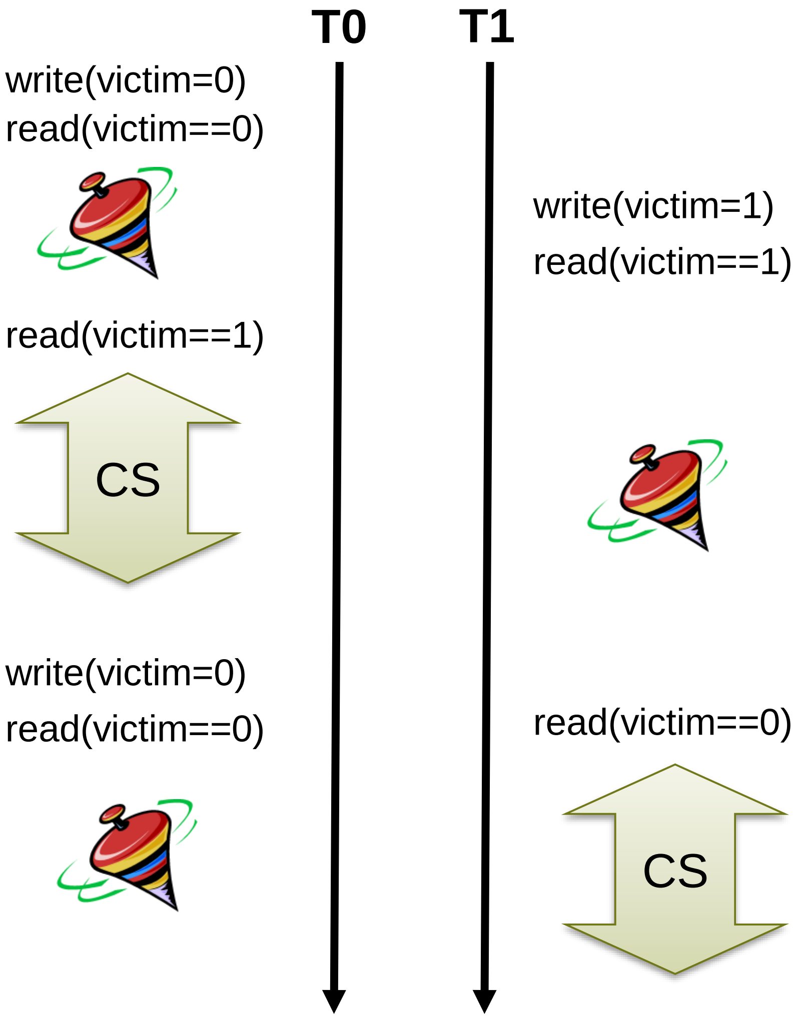

2-threads: LockTwo

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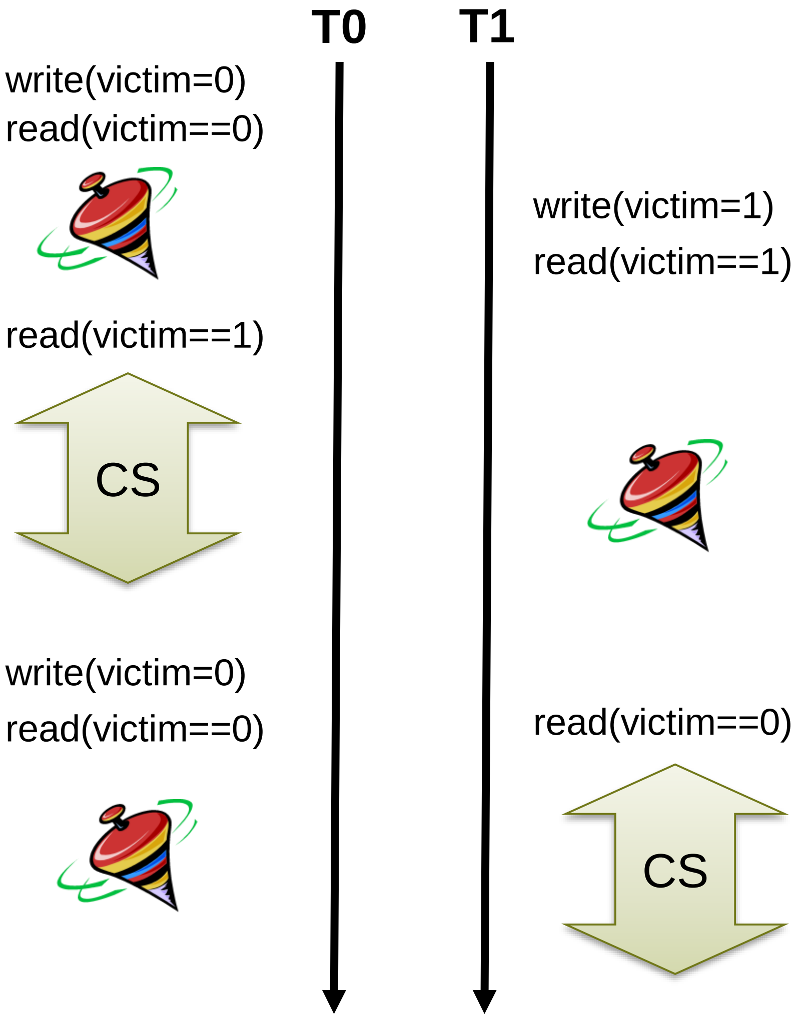

Q: What might be wrong with this lock?

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
}
```

Locking

Locking

- **Safe lock release**
  - RAII in C++
  - try/finally clauses in Java/C#

```
public class BankingSystem {
    ...
    public boolean transferMoney(Account from, Account to, int amount) {
        ...
        first.getLock().lock();
        second.getLock().lock();
        try {
            ...
        } finally {
            first.getLock().unlock();
            second.getLock().unlock();
        }
```

Locking

- **Safe lock release**
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- **Two phase locking**
  - Multiple resources are locked? Lock all of them before performing any computations.

Locking

- **Safe lock release**
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- **Two phase locking**
  - Multiple resources are locked? Lock all

- **Ordered locking**
  - When locking multiple resources, define a total order

```
public class BankingSystem {
    …
    public boolean transferMoney(Account from, Account to, aint amount) {
        Account first, second;
        // Introduce lock ordering:
        if (to.getId() > from.getId()) {
            first = from;        second = to;
        } else {
            first = to;   second = from;
        }
    …
}
```

Locking

- **Safe lock release**
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- **Two phase locking**
  - Multiple resources are locked? Lock all of them before performing any computations.

- **Ordered locking**
  - When locking multiple resources, define a total order

- **Efficient synchronization with atomics**
  - Entering critical section quite often? Locks causing too much overhead?

Locks

Locks

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

Locks

```
void lock() {
  int j = 1 - tid;
  flag[tid] =
  victim =
  while (fla
}
```

Lamport's Bakery

```
volatile int flag[n] = {0,0,…,0};
volatile int label[n] = {0,0,….,0};

void lock() {
  flag[tid] = 1; // request
  label[tid] = max(label[0], ...,label[n-1]) + 1; // take ticket
  while ((∃k != tid)(flag[k] && (label[k],k) <* (label[tid],tid))) {};
}
public void unlock() {
  flag[tid] = 0;
}
```

Locks

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                                   [k] && (label[k],k) <* (label[tid],tid))) {};

  flag[tid] = 0;
}
```

```
bool test_and_set (bool *flag) {
  bool old = *flag;
  *flag = true;
  return old;
} // all atomic!
```

Locks

TATAS

```
volatile int lock = 0;

void lock() {
  do {
    while (lock == 1);
  } while (TestAndSet(&lock) == 1);
}

void unlock() {
  lock = 0;
}
```

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void lock() {
  int j = 1 - tid;
  flag[tid] =
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```

kery

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volatile int flag[n] = {
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void lock() {

  flag[tid] = 0;
}
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bool test_and_set (bool *flag) {
  bool old = *flag;
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Locks

```
volatile int lock = 0;                TATAS

void lock() {
```

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```
volatile
volatile

void loc
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}
```

kery

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```

TATAS + exp backoff

```
volatile int lock = 0;

void lock() {
  while (TestAndSet(&lock) == 1) {
    wait(time);
    time *= 2; // double waiting time
  }
}

void unlock() {
  lock = 0;
}
```

Locks

volatile int lock = 0;

TATAS

S + exp backoff

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{

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b
*
r
} /

Array Queue Lock

```
volatile int array[n] = {1,0,…,0};
volatile int index[n] = {0,0,…,0};
volatile int tail = 0;

void lock() {
  index[tid] = GetAndInc(tail) % n;
  while (!array[index[tid]]); // wait to receive lock
}

void unlock() {
  array[index[tid]] = 0; // I release my lock
  array[(index[tid] + 1) % n] = 1; // next one
}
```

}

Locks

CLH Lock

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

qnode *lck = new qnode; // node owned by lock

void lock(qnode *lck, qnode *qn) {
  qn->succ_blocked = 1;
  qn->prev = FetchAndSet(lck, qn);
  while (qn->prev->succ_blocked);
}

void unlock(qnode **qn) {
  qnode *pred = (*qn)->prev;
  (*qn)->succ_blocked = 0;
  *qn = pred;
}
```

TATAS

off

kery

Locks

MCS Lock

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

qnode *lck = NULL;

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

void unlock(qnode * lck, qnode *qn) {
  if(qn->next == NULL) { // if we're the last waiter
    if(CAS(lck, qn, NULL)) return;
    while(qn->next == NULL); // wait for pred arrival
  }
  qn->next->locked = 0; // free next waiter
  qn->next = NULL;
}
```

TATAS

off

kery

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void lock(qnode *lck, qnode *qn) {
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}
```

Complicated

TATAS

off

kery

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    qn->locked = 1;
    pred->next = q
    while(qn->lock
} }

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Complicated

Difficult to optmize

TATAS

off

kery

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TATAS

Over-optimization can quickly lead to incorrect locks

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TATAS

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

Locks

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Complicated

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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

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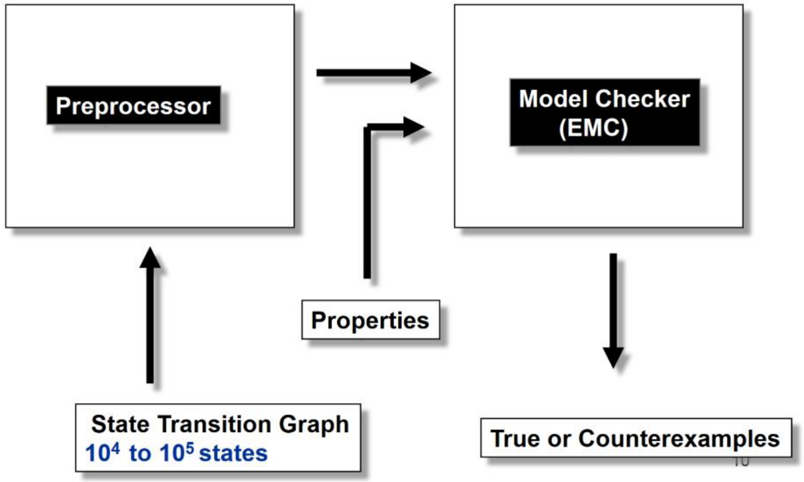
Model checking

- **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 powerful, but model checking can be more practical**




```
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
```

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

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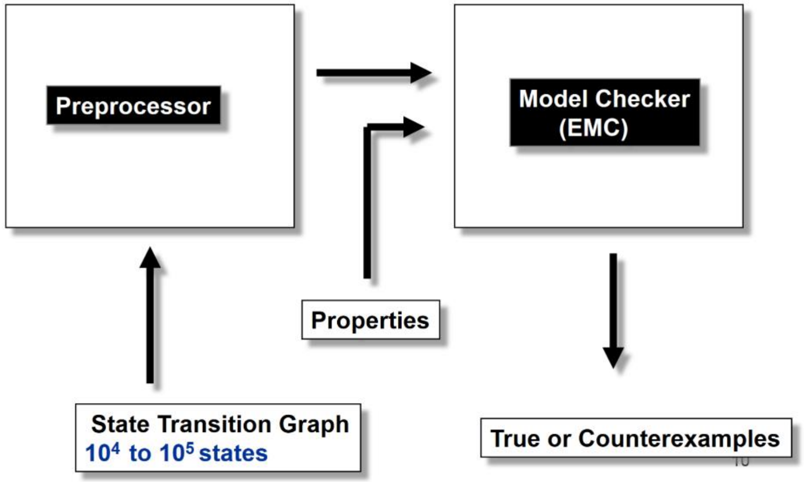
  - The complexity depends on the algorithms itself

- **Deductive proofs are more elegant and powerful, but model checking can be more practical**




```
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
```

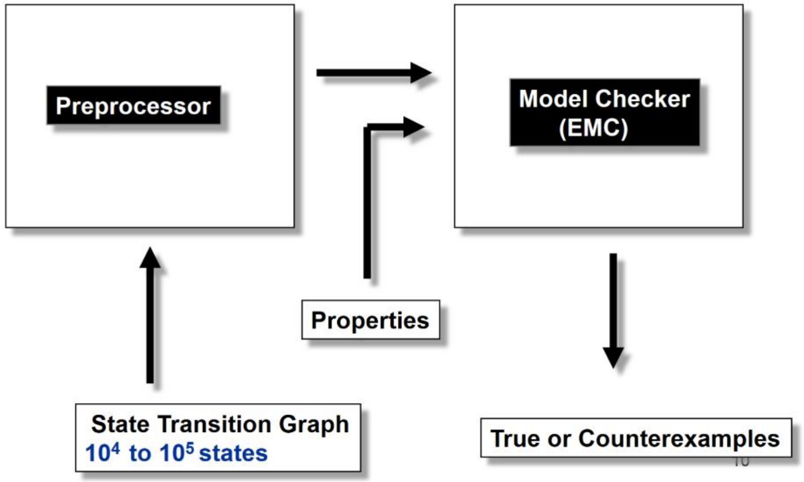
How many states?

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

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 powe**

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

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Space Explosion Problem

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

- **How to handle it?**

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

Space Explosion Problem

- **The system is described as a State Transition Graph**
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- **How to handle it?**

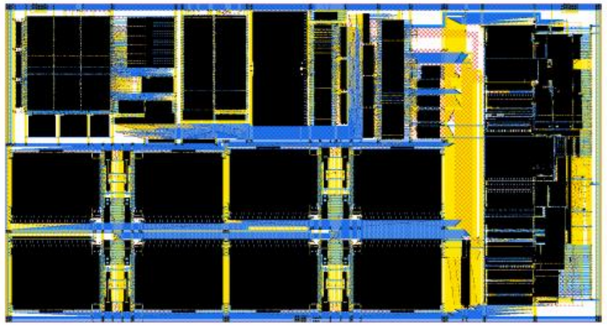
- **Increase the abstraction**

- **Compressed representations**

- **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

Space Explosion Problem



$10^{500,000}$ states

10^{70} atoms

Source: *Probabilistic Model Checking* lectures, Dave Parker.

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() {
    ...            process body
}

proctype Receiver() {
    ...
}

init {
    ...            creates processes
}
```

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

Promela: Hello World

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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;
```

assignment =

```
short s=-1;
```

declaration + initialisation

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

equal test ==

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

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(); }
```

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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);
}
```

Promela: Mutual Exclusion? (2)

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

Promela: Mutual Exclusion? (2)

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        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 -> stat1.1; stat1.2; stat1.3; …
:: choice2 -> stat2.1; stat2.2; stat2.3; …
:: …
:: choicen -> statn.1; statn.2; statn.3; …
od;
```

- **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: 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.

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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

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

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

    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

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<vars> and <consts> can be mixed

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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

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<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**

- **Step by with printing all states:**

```
spin -uN -p –l model
```

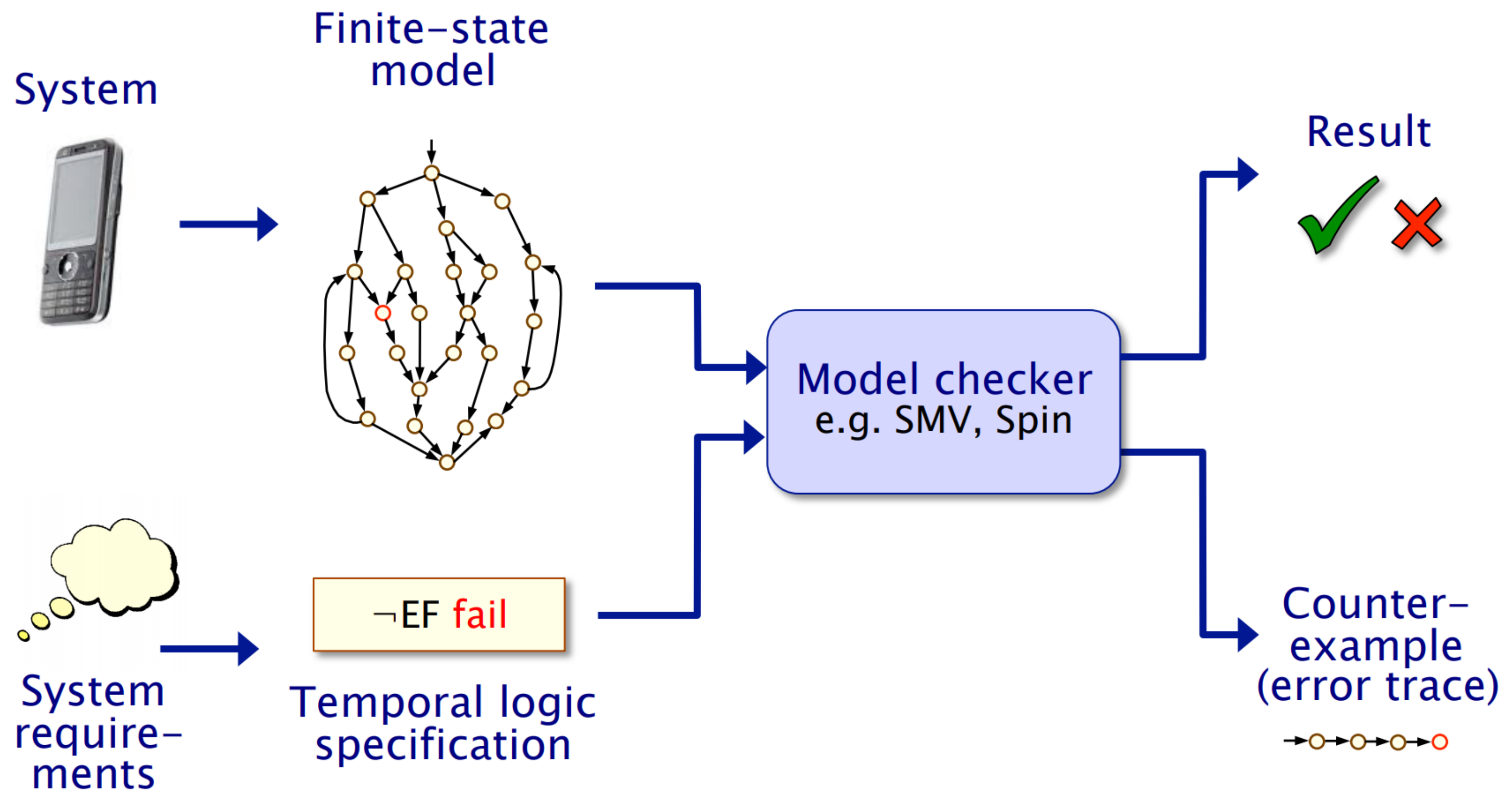
- **Verification mode: analyze all the reachable states**

```
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.

Probabilistic Model Checking



Source: *Probabilistic Model Checking* lectures, Dave Parker.

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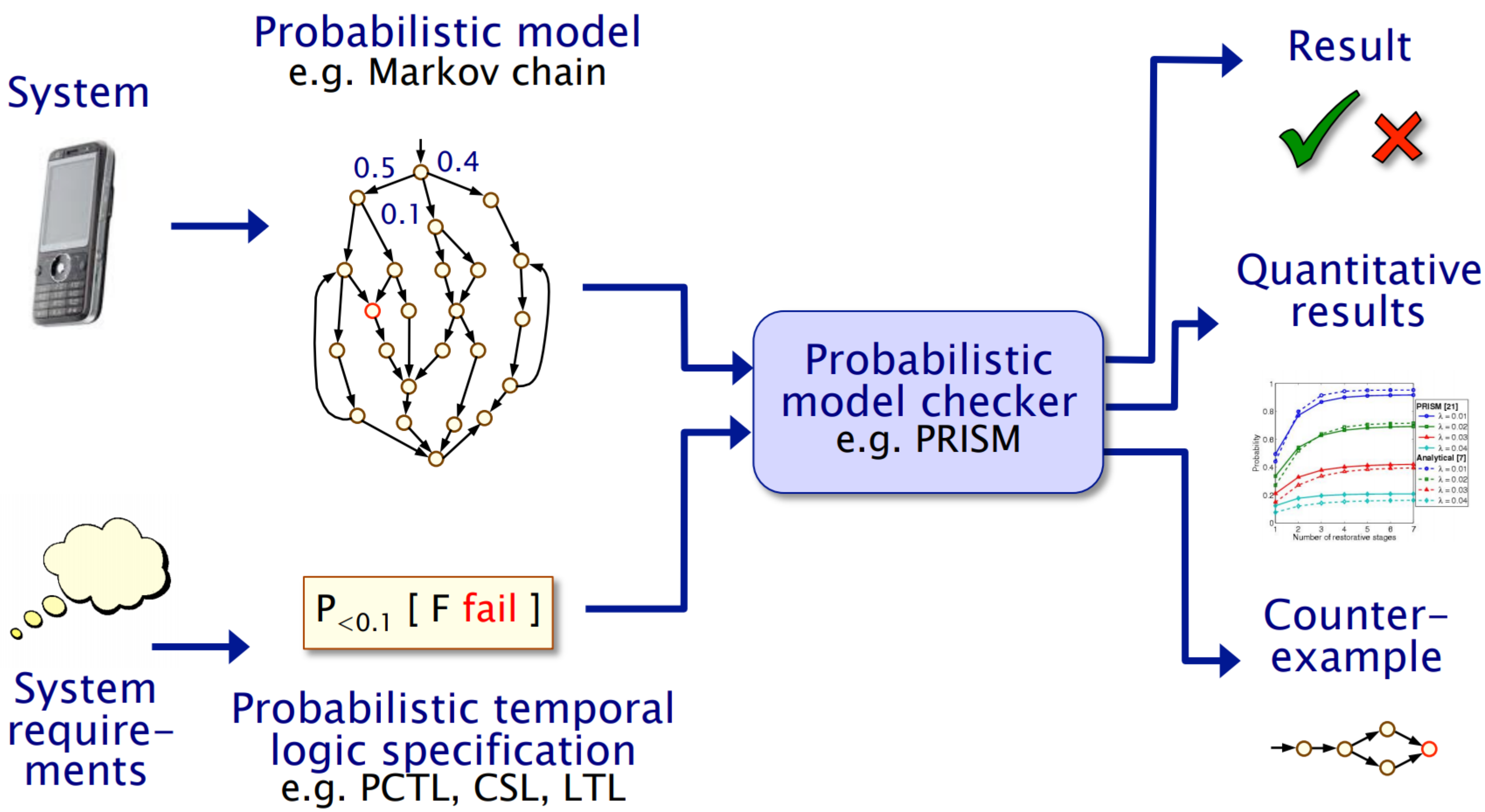

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Why we need probabilistic behaviour?

- **Properties: qualitative vs quantitive**
- **Randomisation – useful to debug distributed algorithms/**
- **Uncertainty – a certain event might happen with small likelihood**

Why we need probabilistic behaviour?

- **Properties: qualitative vs quantitive**
- **Randomisation – useful to debug distributed algorithms/**
- **Uncertainty – a certain event might happen with small likelihood**

“what’s the probability of delivering message in time T?”

“is it true that the probability of recovering from error within T time steps is larger than 0.99?”

“what’s the average power consumption during execution?”

If you want to learn more…

- **SPIN**
  - spinroot.com
  - **Exercises**: http://web.mit.edu/spin_v6.4.7/Doc/1_Exercises.html

- **PRISM – probabilistic model checker**
  - https://www.prismmodelchecker.org/
  - **Lectures on PMC**: https://www.prismmodelchecker.org/lectures/pmc/

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.