On Testing Multithreaded Programs

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0. Overview

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2. Issues in Serial Testing
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1. What is Software Testing

Basic Terms:

- **error** – a mistake made by a developer
- **fault** – errors lead to one or more faults
  - faults are located in the the program
  - fault is the difference between the incorrect program and a correct version
- **failure** – difference between the behavior of the incorrect program and a correct version
  - a fault may lead to zero or more failures

Software Testing and Debugging

Testing (*dynamic testing*) is the process of executing a program with the intent of exhibiting faults.

Monitoring is the process of gathering information about a program's execution.

Debugging is the activity of (1) determining the location and nature of the fault, (2) fixing the fault.

Testing and debugging takes about 50% of development time!

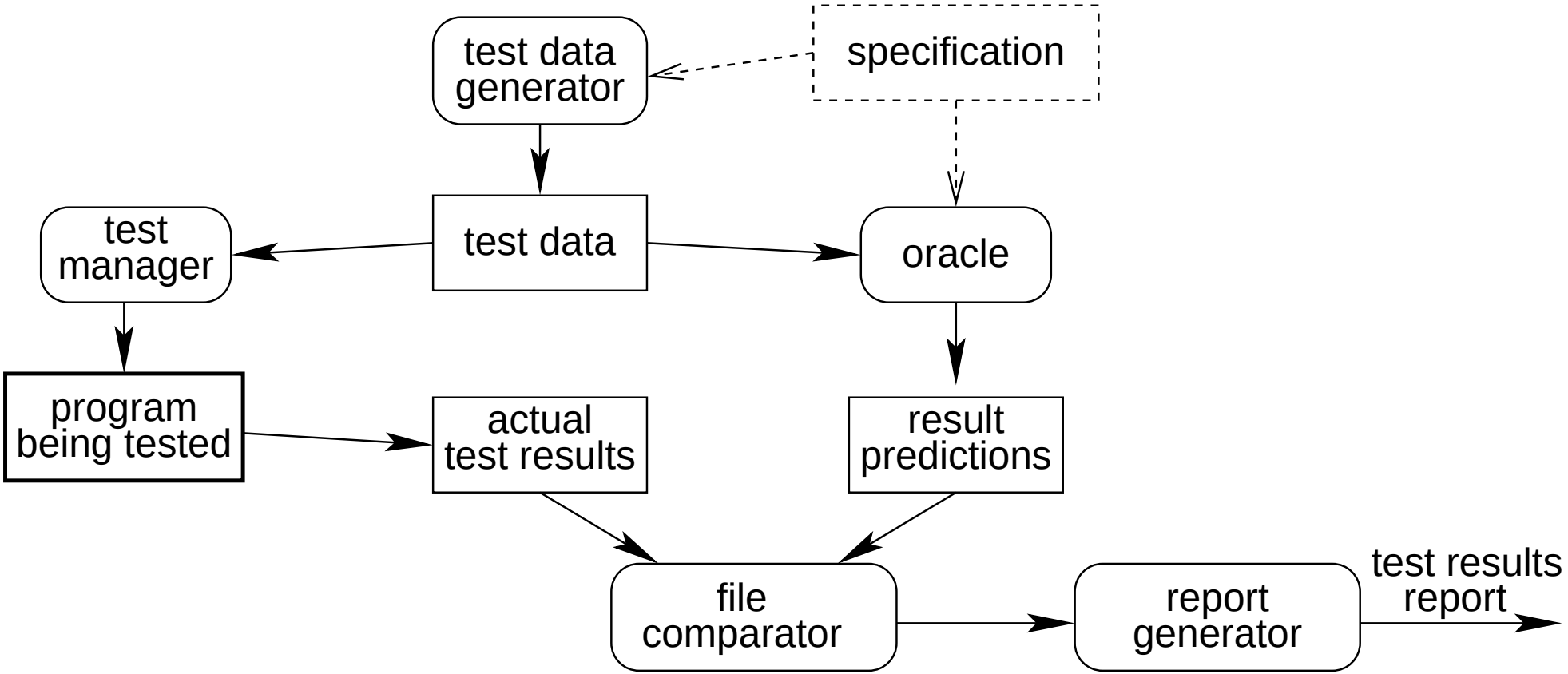
Testing must cost as little as possible $\Rightarrow$ tests should be automatic.

Automated Software Testing

The players:

- **test manager** – controls the test executions
- **test data generator** – generates input data
- **oracle** – generates expected output
- **file comparator** – compares expected and actual output
- **report generator** – reports results

Automated Software Testing (cont.)



2. Issues in Serial Testing

How to design test cases?

- **black-box testing**
  - program to be tested is considered to be a black box
  - test data derived from the specifications
  - exhaustive testing (i.e. use every possible input) is infeasible
  - we are limited to trying a small subset of possible inputs $\Rightarrow$ well selected test cases should (1) maximize yield, (2) cover larger set of test cases

- **white-box testing**
  - test data derived from both the specification and structure of the program

Test Coverage

- **exhaustive path testing** (i.e. executing all possible paths) is infeasible

- **statement coverage**
  - example: **if** (a>1) $\wedge$ (b=0) **then** x := x/a;
  - test case (a=2, b=0) covers both "**if**" and assignment
  - would not exhibit faults in program logic, e.g. "or" instead of "and"

- **branch coverage** – each branch is/is not taken
  - some faults in program logic still not uncovered
  - e.g. test cases (a=2, b=0) and (a=2, b=1)
  - would not exhibit e.g. "a>1" instead of "a>=1"

Test Coverage (cont.)

- **multiple condition coverage**
  - each condition takes both true and false at least once
- **all-du-path coverage**
  - at least one path for each definition-use
- other types of code coverage exist

Measuring Test Coverage

- tools to measure test coverage exist, e.g. GCT (Generic Coverage Tool)
  - instrumentation of code
  - translate instrumented code
  - read and interpret the results
- tests made without measuring typically cover about 55% of the program (Grady 1993)

Measuring Test Coverage (cont.)

Sample GCT output (taken from GCT tutorial):

```
”lc.c”, line 137: operator > might be >=. (L==R)
”lc.c”, line 137: condition 1 (argc, 1) was taken TRUE 43, FALSE 0 times
”lc.c”, line 139: condition 1 (<...>[...], 1) was taken TRUE 0, FALSE 14
”lc.c”, line 153: if was taken TRUE 0, FALSE 29 times.
”lc.c”, line 162: loop zero times: 0, one time: 19, many times: 10.
”lc.c”, line 172: if was taken TRUE 0, FALSE 43 times.
```

3. Testing Concurrent Programs

- testing and debugging concurrent programs is more difficult
  - concurrent faults not present in serial programs
  - two executions of a program with the same data do not have to be identical
  - testing: concurrent faults are hard to exhibit
  - debugging: concurrent faults are hard to reproduce

Testing Concurrent Programs (cont.)

Concurrent faults:

- **safety faults** – race conditions, can be avoided by proper synchronization
  - common cause: the programmer forgets to lock
  - hard to detect
- **liveness faults**, e.g. starvation and deadlock
  - common cause: the programmer forgets to unlock (leads to a halt)
  - deadlock is easy to detect: create resource allocation graph, deadlock manifests as a cycle in the graph

Race Conditions

- formally specified first by Netzer (1992)

- there are two kinds of race conditions
  - **general races** – failures in programs intended to be deterministic
    - cause nondeterministic execution
  - **data races** – failures in nondeterministic programs
    - cause nondeterministic execution of critical sections accessing and updating shared data
  - data races are easier to detect (they are a local property, can be detected from the execution trace)

Data Race Detection

Types of race detection:

- static analysis – applied at compile time
  - undecidable for unrestricted programs
- post mortem analysis – collect trace information, analyze
  - problem – traces tend to be huge, we cannot store everything
- on-the-fly analysis – trace is analyzed as it is generated
  - traces can include shared memory access
  - problem – slows the application down significantly

The probe effect

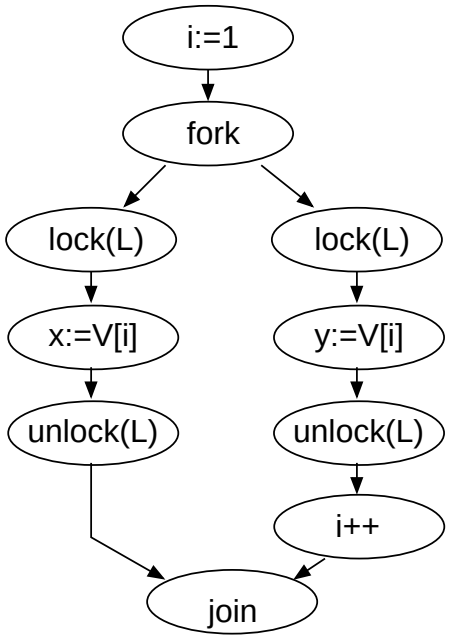
- any SW technique for collecting data perturbs the application
- more data $\Rightarrow$ large instrumentation overhead $\Rightarrow$ collected data no longer match the original program (e.g. the concurrent failure disappears)

Finding Races in Execution Traces

- most techniques based on state enumeration
- execution traces $\equiv$ branch-free programs
  - branches are ”hard wired” then trace is generated
  - monotonic synchronization constructs = branch-free program either always terminates or always deadlocks in the same state
  - if synchronization constructs are monotonic, exhibited races can be found in P
  - single semaphore – P
  - other primitives – NP hard or co-NP-hard

Example: Anne Dinning and Edith Schonberg

Dynamic on-the-fly algorithm to detect race conditions in programs with fork/join and locks



Example (cont.)

- Dinning-Schonberg algorithm reports a race if:
  - shared variable is accessed in two unordered blocks
  - at least one of the accesses is a write
  - intersection of lock covers is empty

Limitation of the Dinning-Schonberg algorithm:

- limited to programs with critical sections synchronized using lock and unlock (not applicable to other synchronization primitives)

- will not find race conditions in programs with internal non-determinism (races in execution paths not taken)

4. Test Adequacy Criteria

- traditional test coverage methods can be used for serializations, but will not uncover concurrent faults
- branch coverage?
  - threads may or may not be independent
  - we cannot cover branches in one thread independently of the other
- all-du-path coverage?
  - we obtain partial paths (definition $\rightarrow$ post, wait $\rightarrow$ use)
  - some work done (e.g. Yang and Pollock 1998), but has (inherent?) problems

Test Adequacy Criteria (cont.)

- liveness
  - 0, 1, more threads suspended? (e.g. Long 2003)
  - state transition coverage? (Taylor, Levine, and Kelly 1992)
    - includes control and synchronization, omits data values etc.
    - state explosion problem, hides sequential activities in each state
  - interaction coverage? (Katayama, Furukawa, and Ushijima 1997 for Ada task-types)

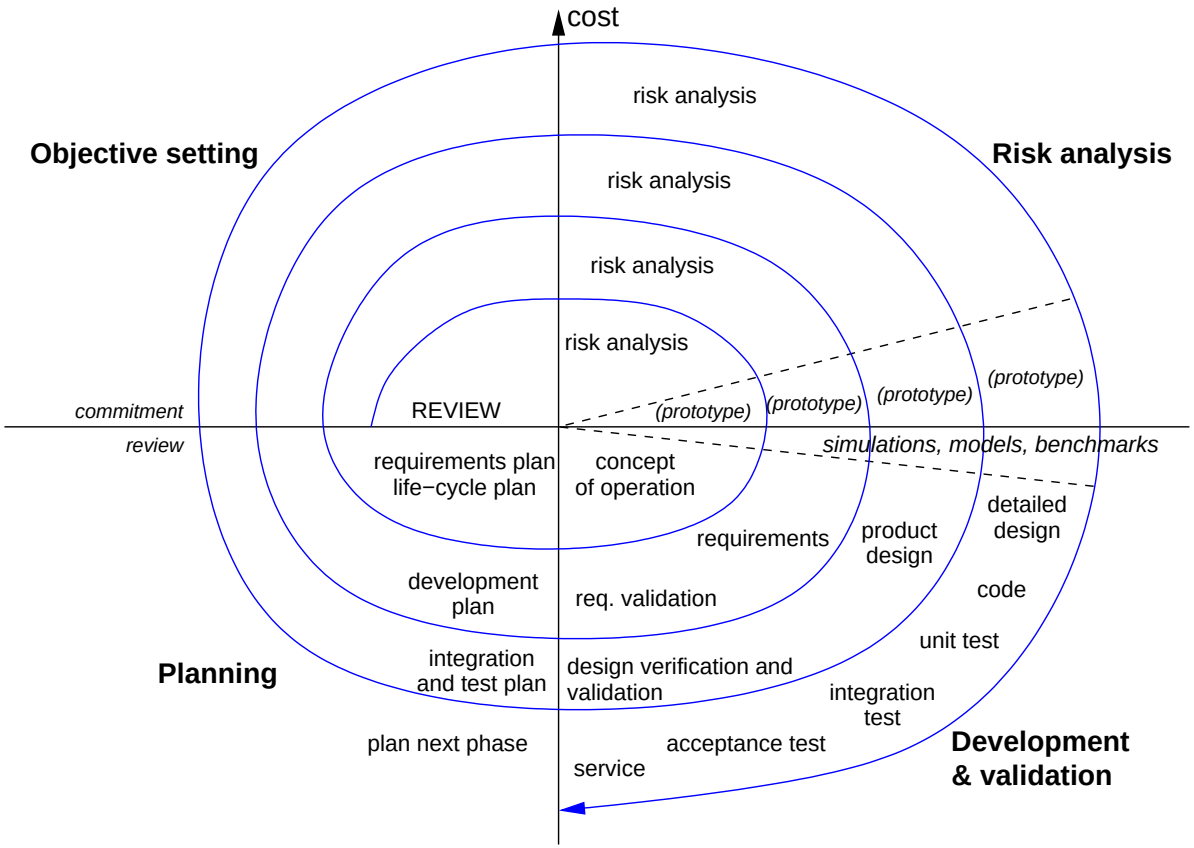
- race coverage?
  - contention on variables
  - GCT can measure whether two methods were executed at the same time, ConTest measures whether a context switch occurred when executing a method

Improving Test Yield

- probe effect (Gait 1986)
  - inserted delays can hide/exhibit failures
  - ”noise maker” – enforces different interleavings of events on each execution
  - delays should be inserted to useful places (synchronization events, communication events, thread creation), delay duration needs to change
  - problem: exponential number of interleavings, heuristics needed to find the most useful ones
- existing utilities: ConAn, ConTest

5. Research Plan

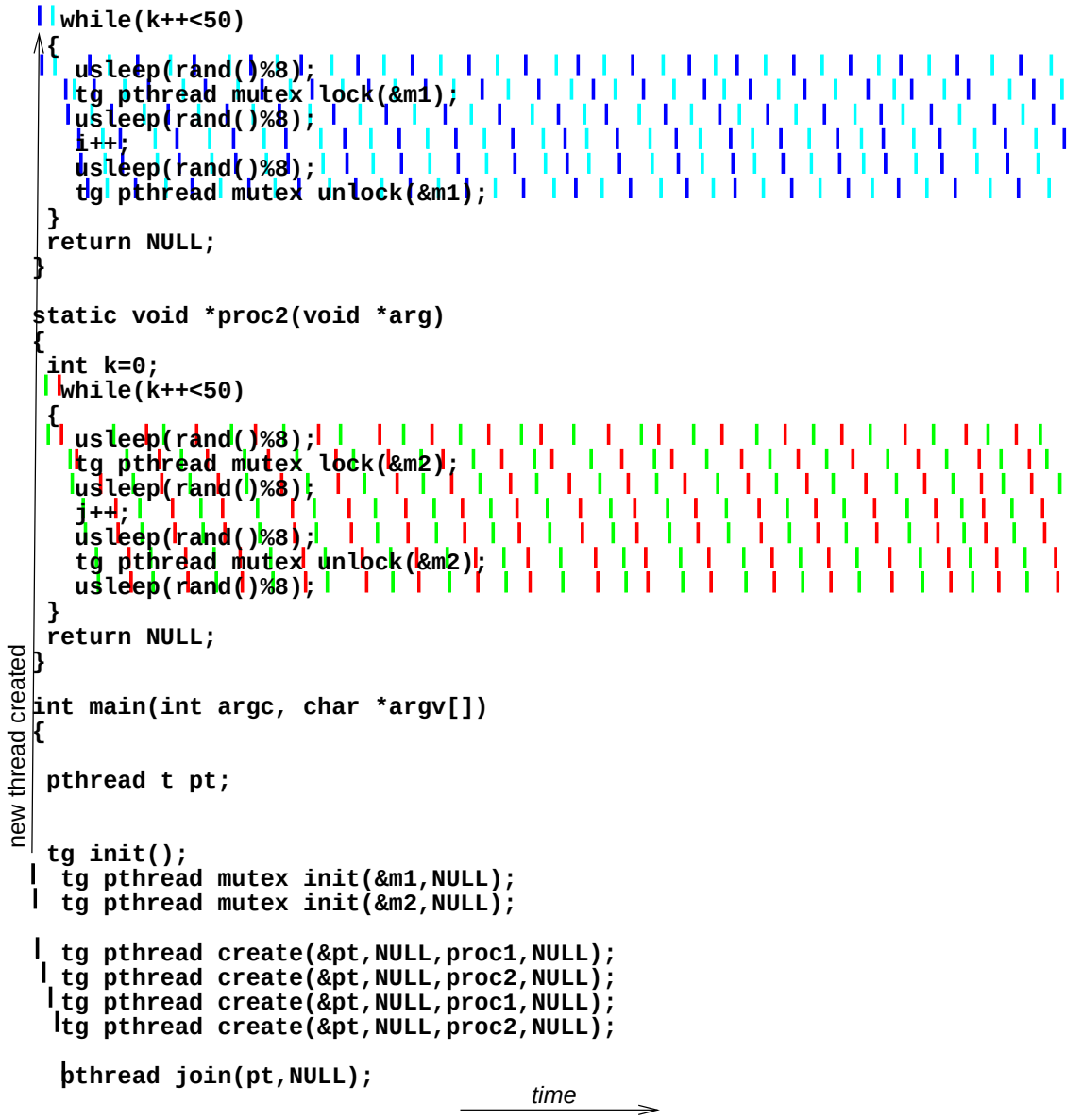
Goal of the project: support for testing multithreaded applications.



Steps for the First Cycle

- try to understand the problem
  - create a benchmark (set of test cases)
  - develop support for visualization
  - look for patterns
- develop prototypes
  - prototype instrumentation injecting ”noise”
  - look for the ”alternatives” (utilize the visualization)
- find the solution at the high level of granularity
  - refine for lower level of granularity (e.g. adapt to race coverage)
- automate instrumentation, possibly for C# or Java

Tracing & Visualization of Trace Logs



Tracing & Visualization of Trace Logs

```
sim_logger(SIM_LOGENTER, "gmi_chwrite(\"%s\", %s, %u) \"%s\"\n",
  name, (data.type == GMI_EOF)? "EOF" : "data",
  pktno, sim_getattr7name());
sim_logger(SIM_LOGVALUE,
  "gmi_chwrite: data = { type=%u, tag=%u, nelem=%u, elsize=%u }",
  data.type, data.tag, data.nelem, data.elsize);
chan = sim_getobject(name, SIM_OBJ_K);
if (chan==NULL || chan==(void*)1 || chan==(void*)2)
{
  sim_logger(SIM_LOGERR,
    "gmi_chwrite failed: access to nonexistent channel %s",
    name);
  sim_setevent(SIM_SETEV_EXIT, GMI_EV_LIBARG,
    "gmi_chwrite: bad argument (name)");
}

if (data.type == GMI_EOF) /* EOF requires special handling. */
{
sim_chcond *tc;
  sim_barsync(chan+1, chan->writers);
  sim_mutex_lock(&(chan->mutex));
 /* This should be done only once. */
 if (chan->iseof == 0)
 {
   chan->iseof = 1;
   for (tc = chan->cond; tc != NULL; tc = tc->prev)
   {  sim_cond_signal(&(tc->cond));}
 }
 sim_mutex_unlock(&(chan->mutex));
 return;
}

ent = sim_malloc(sizeof(sim_chunk));
ent->pktno = pktno;
/* Make a deep copy of the data. */
ent->d.data = data;
ent->d.data = sim_malloc(data.nelem * data.elsize);
memcpy(ent->d.data, data.data, data.nelem * data.elsize);
sim_mutex_lock(&(chan->mutex));
/* Ignore data if EOF. */
if (chan->iseof != 0)
{
  sim_logger(SIM_LOGERR,
    "gmi_chwrite: write ignored in EOF state");
  sim_mutex_unlock(&(chan->mutex));
  return;
}
/* Insert new entry into channel's list of chunks. */
ent->prev = NULL;
ent->next = chan->entries;
if (chan->entries != NULL)
{
  assert(chan->entries->prev == NULL);
  chan->entries->prev = ent;
}
chan->entries = ent;
if (chan->cond != NULL) /* Someone may wait for us. */
{
sim_chcond *tc;
  for (tc=chan->cond; tc!=NULL && tc->pktno!=pktno; tc=tc->prev)
  ;
  if (tc != NULL)
  {
    sim_logger(SIM_LOGINTRN,
      "gmi_chwrite: waking up thread %u", tc->thid);
    sim_cond_signal(&(tc->cond));
  }
}
```

Histogram

```
  sim_logger(SIM_LOGENTER, "gmi_chwrite(\"%s\", %s, %u) \"%s\"",
  name, (data.type == GMI_EOF)? "EOF" : "data",
  pktno, sim_getattr(name));
  sim_logger(SIM_LOGVALUE,
   "gmi_chwrite: data = { type=%u, tag=%u, nelem=%u, elsize=%u }",
   data.type, data.tag, data.nelem, data.elsize);
  chan = sim_getobject(name, SIM_OBJ_K);
  if (chan == NULL || chan == (void*)1 || chan == (void*)2)
  {
    sim_logger(SIM_LOGERR,
     "gmi_chwrite failed: access to nonexistent channel %s",
     name);
    sim_setevent(SIM_SETEV_EXIT, GMI_EV_LIBARG,
     "gmi_chwrite: bad argument (name)");
  }
  if (data.type == GMI_EOF) /* EOF requires special handling. */
  {
  sim_chcond *tc;
    sim_barsync(chan+1, chan->writers);
    sim_mutex_lock(&(chan->mutex));
   /* This should be done only once. */
   if (chan->iseof == 0)
   {
    chan->iseof = 1;
     for (tc = chan->cond; tc != NULL; tc = tc->prev)
     {  sim_cond_signal(&(tc->cond));}
   }
    sim_mutex_unlock(&(chan->mutex));
    return;
  }
  ent = sim_malloc(sizeof(sim_chunk));
  ent->pktno = pktno;
  /* Make a deep copy of the data. */
  ent->d = data;
  ent->d.data = sim_malloc(data.nelem * data.elsize);
  memcpy(ent->d.data, data.data, data.nelem * data.elsize);
  sim_mutex_lock(&(chan->mutex));
  /* Ignore data if EOF. */
  if (chan->iseof != 0)
  {
    sim_logger(SIM_LOGERR,
     "gmi_chwrite: write ignored in EOF state");
    sim_mutex_unlock(&(chan->mutex));
    return;
  }
  /* Insert new entry into channel's list of chunks. */
  ent->prev = NULL;
  ent->next = chan->entries;
  if (chan->entries != NULL)
  {
    assert(chan->entries->prev == NULL);
    chan->entries->prev = ent;
  }
  chan->entries = ent;
  if (chan->cond != NULL) /* Someone may wait for us. */
  {
  sim_chcond *tc;
    for (tc=chan->cond; tc!=NULL && tc->pktno!=pktno; tc=tc->prev)
    if (tc != NULL)
    {
      sim_logger(SIM_LOGINTRN,
       "gmi_chwrite: waking up thread %u", tc->thid);
      sim_cond_signal(&(tc->cond));
    }
  }
  sim_stat_data1("gmi_chwrite", chan->stat, data);
  sim_mutex_unlock(&(chan->mutex));
  sim_yield();
}
```

Switch Occurrences (Slow CPU)

```
        chan = simobject(name, SIM_OBJ_K);
        if (chan == NULL || chan == (void*)1 || chan == (void*)2)
        {
                sim logger(SIM_LOGERR,
                           "gmi_chwrite failed: access to nonexistent channel %s",
                           name);
                sim setevent(SIM_SETEV_EXIT, GMI_EV_LIBARG,
                             "gmi_chwrite: bad argument (name)");
        }
        if (data.type == GMI_EOF) /* EOF requires special handling. */
        {
                sim chcond *tc;
                sim barsync(chan+1, chan->writers);
                sim mutex_lock(&(chan->mutex));
                /* This should be done only once. */
                if (chan->iseof == 0)
                {
                        chan->iseof = 1;
                        for (tc = chan->cond; tc != NULL; tc = tc->prev)
                                { sim_cond_signal(&(tc->cond));}
                }
                sim_mutex_unlock(&(chan->mutex));
                return;
        }
        ent = sim_malloc(sizeof(sim_chunk));
        ent->pktno = pktno;
        /* Make a deep copy of the data. */
        ent->d = data;
        ent->d.data = sim_malloc(data.nelem * data.elsize);
        memcpy(ent->d.data, data.data, data.nelem * data.elsize);
        sim_mutex_lock(&(chan->mutex));
        /* Ignore data if EOF. */
        if (chan->iseof != 0)
        {
                sim_logger(SIM_LOGERR,
                           "gmi_chwrite: write ignored in EOF state");
                sim_mutex_unlock(&(chan->mutex));
                return;
        }
        /* Insert new entry into channel's list of chunks. */
        ent->prev = NULL;
        ent->next = chan->entries;
        if (chan->entries != NULL)
        {
                assert(chan->entries->prev == NULL);
                chan->entries->prev = ent;
        }
        chan->entries = ent;
        if (chan->cond != NULL) /* Someone may wait for us. */
        {
                sim_chcond *tc;
                for (tc=chan->cond; tc!=NULL && tc->pktno!=pktno; tc=tc->prev)
                if (tc != NULL)
                {
                        sim_logger(SIM_LOGINTRN,
                                   "gmi_chwrite: waking up thread %u", tc->thid);
                        sim_cond_signal(&(tc->cond));
                }
        }
        sim_stat_data1("gmi_chwrite", chan->stat, data);
        sim_mutex_unlock(&(chan->mutex));
        sim_yield();
}
```

Switch Occurrences (Fast CPU)

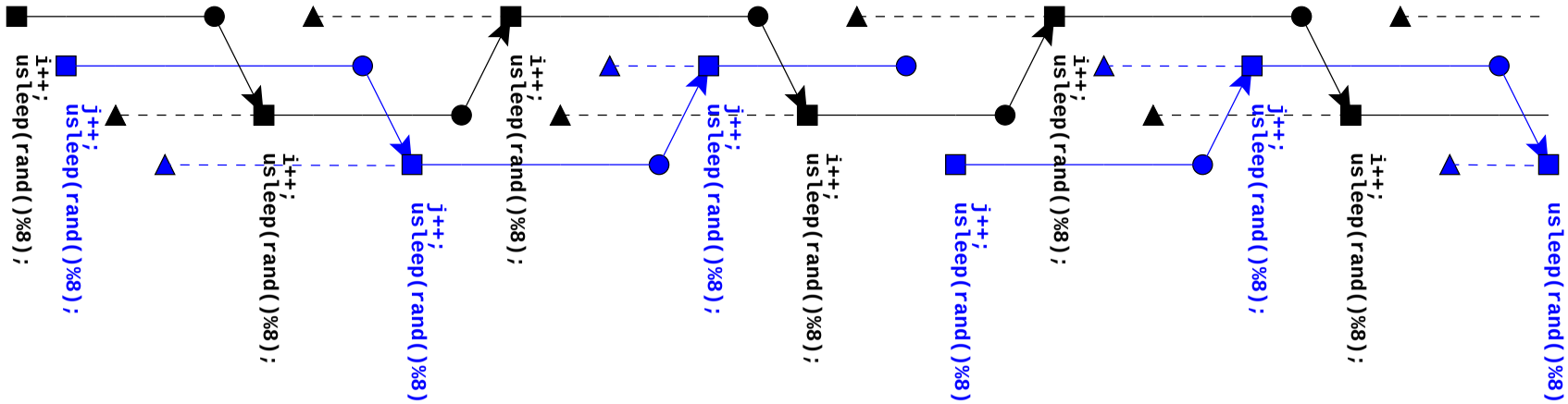
```
        chan = sim_getobject(name, SIM_OBJ_K);
        if (chan == NULL || chan == (void*)1 || chan == (void*)2)
        {
                sim_logger(SIM_LOGERR,
                           "gmi_chwrite failed: access to nonexistent channel %s",
                           name);
                sim_setevent(SIM_SETEV_EXIT, GMI_EV_LIBARG,
                             "gmi_chwrite: bad argument (name)");
        }
        if (data.type == GMI_EOF) /* EOF requires special handling. */
        {
                sim_chcond *tc;
                sim_barsync(chan+1, chan->writers);
                sim_mutex_lock(&(chan->mutex));
                /* This should be done only once. */
                if (chan->iseof == 0)
                {
                        chan->iseof = 1;
                        for (tc = chan->cond; tc != NULL; tc = tc->prev)
                                { sim_cond_signal(&(tc->cond));}
                }
                sim_mutex_unlock(&(chan->mutex));
                return;
        }
        ent = sim_malloc(sizeof(sim_chunk));
        ent->pktno = pktno;
        /* Make a deep copy of the data. */
        ent->d = data;
        ent->d.data = sim_malloc(data.nelem * data.elsize);
        memcpy(ent->d.data, data.data, data.nelem * data.elsize);
        sim_mutex_lock(&(chan->mutex));
        /* Ignore data if EOF. */
        if (chan->iseof != 0)
        {
                sim_logger(SIM_LOGERR,
                           "gmi_chwrite: write ignored in EOF state");
                sim_mutex_unlock(&(chan->mutex));
                return;
        }
        /* Insert new entry into channel's list of chunks. */
        ent->prev = NULL;
        ent->next = chan->entries;
        if (chan->entries != NULL)
        {
                assert(chan->entries->prev == NULL);
                chan->entries->prev = ent;
        }
        chan->entries = ent;
        if (chan->cond != NULL) /* Someone may wait for us. */
        {
                sim_chcond *tc;
                for (tc=chan->cond; tc!=NULL && tc->pktno!=pktno; tc=tc->prev)
                if (tc != NULL)
                {
                        sim_logger(SIM_LOGINTRN,
                                   "gmi_chwrite: waking up thread %u", tc->thid);
                        sim_cond_signal(&(tc->cond));
                }
        }
        sim_stat_data1("gmi_chwrite", chan->stat, data);
        sim_mutex_unlock(&(chan->mutex));
        sim_yield();
}
```

Switch Occurrences (multiprocessor)

```
        chan = sim_getobject(name, SIM_OBJ_K);
        if (chan == NULL || chan == (void*)1 || chan == (void*)2)
        {
                sim_logger(SIM_LOGERR,
                           "gmi_chwrite failed: access to nonexistent channel %s",
                           name);
                sim_setevent(SIM_SETEV_EXIT, GMI_EV_LIBARG,
                             "gmi_chwrite: bad argument (name)");
        }
        if (data.type == GMI_EOF) /* EOF requires special handling. */
        {
                sim_chcond *tc;
                sim_barsync(chan+1, chan->writers);
                sim_mutex_lock(&(chan->mutex));
                /* This should be done only once. */
                if (chan->iseof == 0)
                {
                        chan->iseof = 1;
                        for (tc = chan->cond; tc != NULL; tc = tc->prev)
                                { sim_cond_signal(&(tc->cond));}
                }
                sim_mutex_unlock(&(chan->mutex));
                return;
        }
        ent = sim_malloc(sizeof(sim_chunk));
        ent->pktno = pktno;
        /* Make a deep copy of the data. */
        ent->d = data;
        ent->d.data = sim_malloc(data.nelem * data.elsize);
        memcpy(ent->d.data, data.data, data.nelem * data.elsize);
        sim_mutex_lock(&(chan->mutex));
        /* Ignore data if EOF. */
        if (chan->iseof != 0)
        {
                sim_logger(SIM_LOGERR,
                           "gmi_chwrite: write ignored in EOF state");
                sim_mutex_unlock(&(chan->mutex));
                return;
        }
        /* Insert new entry into channel's list of chunks. */
        ent->prev = NULL;
        ent->next = chan->entries;
        if (chan->entries != NULL)
        {
                assert(chan->entries->prev == NULL);
                chan->entries->prev = ent;
        }
        chan->entries = ent;
        if (chan->cond != NULL) /* Someone may wait for us. */
        {
                sim_chcond *tc;
                for (tc=chan->cond; tc!=NULL && tc->pktno!=pktno; tc=tc->prev)
                if (tc != NULL)
                {
                        sim_logger(SIM_LOGINTRN,
                                   "gmi_chwrite: waking up thread %u", tc->thid);
                        sim_cond_signal(&(tc->cond));
                }
        }
        sim_stat_data1("gmi_chwrite", chan->stat, data);
        sim_mutex_unlock(&(chan->mutex));
        sim_yield();
}
```

Visualization of Event Ordering

■ – pthread_mutex_lock()
● – pthread_mutex_unlock()
▲ – thread suspended while trying to lock



- i++ (resp. j++) are protected by mutexes m1 (resp. m2)

Lessons learned so far

- complete traces tend to be huge, really :-)
- faster single-CPU computers $\Rightarrow$ less probable to exhibit a concurrent fault
- multiprocessors $\Rightarrow$ more likely to uncover faults