PARALLEL COMPUTING

Shared Memory

Armin Biere

Version WS 2021.3

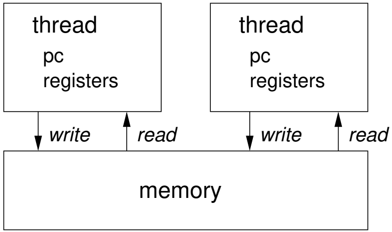
JOHANNES KEPLER
UNIVERSITY LINZ

Why Shared Memory?

- wide-spread availability of multi-core
  - in servers for more than 20 years
  - desktop for more than 15 years
  - GPU computing for more than 15 years
  - smart phones for more than 10 years
- power limits in CMOS technology
  - around 2005 frequency scaling stopped
  - Moore's law still continued to hold
  - more cores instead of higher frequency

- threads
  - "known" programming model
  - similar to sequential model
  - but with globally shared memory
  - and multiple processing units
- processes
  - classical but more complicated
  - fork / join paradigm
  - communication over files / pipes
  - `mmap (..., MAP_SHARED, ...)`

Shared Memory Programming Model



- programs / processes / threads
  - local architectural (CPU) state
  - including registers / program counter
  - shared heap for threads
  - shared memory for processes
- communicate over **global** memory
  - think globally shared variables
- *read* and *write* atomic
  - only for machine word values (and pointers)
  - need other synchronization mechanisms
- solution for mutual exclusion needed

Data Race

```c
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

pthread_t t0, t1;
int x;

void *
incx (void * dummy)
{
  x++;
  return 0;
}
```

```c
int
main (void)
{
  pthread_create (&t0, 0, incx, 0);
  pthread_create (&t1, 0, incx, 0);
  pthread_join (t0, 0);
  pthread_join (t1, 0);
  printf ("%d\n", x);
  return 0;
}
```

Data Race

- this code already gives some ideas about pthreads
- increment function `incx` just increments the global variable `x` (without locking)
- the `main` function creates two threads running `incx`
- then waits for them to finish (joins with first thread `t0` first, then with second `t1`)
- if first thread finishes executing `incx` before second starts then there is no problem
- incrementing twice should always yield 2 as output
- but there is a potential data race
  1. first thread `t0` reads value 0 of `x` into local register `r0`
  2. also increments its local copy in `r0` to value 1
  3. second thread `t1` reads old value 0 of `x` into its local register `r1`
  4. also increments its local copy in `r1` to value 1
  5. now first thread `t0` writes back `r0` to the global variable `x` with value 1
  6. finally second thread `t1` writes back `r0` to the global variable `x` with value 1
- testing with massif load (schedule steering)

  `valgrind --tool=helgrind` or `gcc -fsanitize=thread`

Avoiding Data Races Through Locking / Mutual Exclusion

```
void *
incx (void * dummy)
{
  lock ();
  int tmp = x;
  tmp++;
  x = tmp;
  unlock ();
  return 0;
}
```

How to implement locking?

- will first look at software only solutions
- hardware solutions much more efficient

Eraser / Lock-Set Algorithm

Stefan Savage, Michael Burrows, Greg Nelson, Patrick Sobalvarro, Thomas E. Anderson:
Eraser: A Dynamic Data Race Detector for Multithreaded Programs. ACM Trans. Comput. Syst. 15(4):
391-411 (1997)

- check for "locking discipline"
  - shared access protected by at least one lock
  - collect lock sets at read and write events
  - check that intersection of lock sets non-empty
- if a lock-set becomes empty
  - produce improper locking warning (potential data race)
  - even though the actual race might not have occurred
- initialization is tricky (phases)
  - spurious warnings
  - only some can surpressed automatically
- for instance implemented in `helgrind`
- major problem is that it needs "sandboxing" (interpreting memory accesses)

Mutual Exclusion with Deadlock

```c
#include ...

pthread_t t0, t1;
int x;

int id[]   = { 0, 1 };
int flag[] = { 0, 0 };

void lock (int * p) {
  int me = *p,
  int other = !me;
  flag[me] = 1;
  while (flag[other])
    ;
}

void unlock (int * p) {
  int me = *p;
  flag[me] = 0;
}
```

```c
void *
incx (void * p)
{
  lock (p);
  x++;
  unlock (p);
  return 0;
}

int
main (void)
{
  pthread_create (&t0, 0, incx, &id[0]);
  pthread_create (&t1, 0, incx, &id[1]);
  pthread_join (t0, 0);
  pthread_join (t1, 0);
  printf ("%d\n", x);
  return 0;
}
```

Deadlock

- data race
  - uncoordinated access to memory
  - interleaved partial views
  - inconsistent global state (incorrect)
  - “always consistent” = **safety** property
  - avoided by locking
  - which in turn might slow-down application
- deadlock
  - two threads wait for each other
  - each one needs the other to “release its lock” to move on
  - “no deadlock” = **liveness** property
  - does not necessarily need sandboxing
  - might be easier to debug
  - might actually not be that bad (“have you tried turning it off and on again?”)
  - more fine-grained versions later
- debugging dead-lock
  - tools allow to find locking cycles
  - run your own cycle checker after wrapping lock / unlock
  - attach debugger to deadlocked program

Mutual Exclusion with Deadlock

```
#include ...

pthread_t t0, t1;
int x;

int id[]   = { 0, 1 };
int victim = 0;

void lock (int * p) {
  int me = *p;
  victim = me;
  while (victim == me)
    ;
}

void unlock (int * p) {
}
```

- previous version
  - flag to go first
  - hope nobody else has the same idea at the same time
  - but check that and if this is not the case proceed
  - deadlock under contention
- this version
  - even more passive / helpful
  - always let the other go first
  - tell everybody that you are waiting
  - wait until somebody else waits too
  - almost always deadlocks (without contention)
- the Peterson algorithm combines both ideas

Peterson Algorithm

```
void lock (int * p) {
  int me = *p;
  int other = !me;
  flag[me] = 1;
  victim = me;
  // __sync_synchronize ();
  while (flag[other] && victim == me)
    ;
}

void unlock (int * p) {
  int me = *p;
  flag[me] = 0;
}
```

actually broken on real modern hardware

- without the memory fence
- because read in other thread can be reordered before own write (even for restricted x86 memory model)

expected:

0: *write* (flag[0], 1)	1: *write* (flag[1], 1)
0: *write* (victim, 0)	1: *write* (victim, 1)
0: *read* (flag[1]) = 1	1: *read* (flag[0]) = 1

possible:

0: *read* (flag[1]) = 0	1: *read* (flag[0]) = 0
0: *write* (flag[0], 1)	1: *write* (flag[1], 1)
0: *write* (victim, 0)	1: *write* (victim, 1)

Mutual Exclusion Algorithms

- classical “software-only” algorithms
  - more of theoretical interest only now
  - because memory model of multi-core machines weak (reorders reads and writes)
  - but would be on reorder-free hardware still not really efficient (in space and time)
- need hardware support anyhow
  - various low-level (architecture) depedent primitives
  - atomic increment, bit-set, compare-and-swap and memory fences
  - better use platform-independent abstractions, such as pthreads
- we will latter see how-those low-level primitives can be used

Sequential Consistency

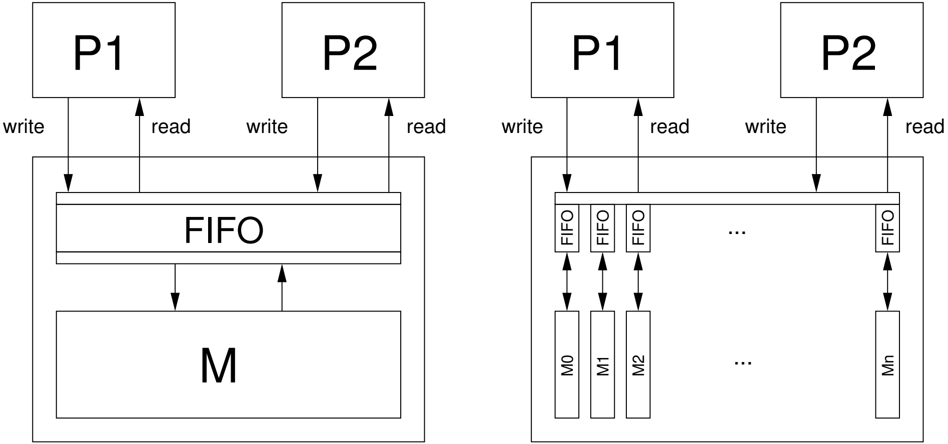
Leslie Lamport:
How to Make a Multiprocessor Computer That Correctly Executes Multiprocess Programs.
IEEE Trans. Computers 28(9): 690-691 (1979)

- systems with processors (cores) and memories (caches)
  - think HW: processors and memories work in parallel
  - processors read (fetch) values and write (store) computed values to memories
  - common abstraction: consider each memory address as single memory module
- (single) processor **sequential** iff programs (reads / writes) executed sequentially
  - sequentially means without parallelism
  - between memories and the single processor
- processors **sequentially consistent** iff

  every parallel execution of programs
  can be reordered into a sequential execution
  such that sequential semantics of programs and memories are met

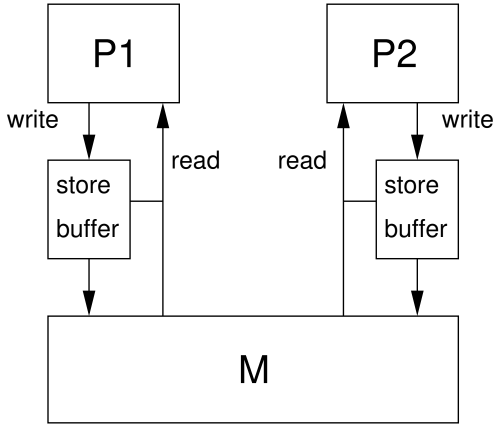
  - sequential (single) program semantics: read / writes executed in program order
  - sequential (single) memory semantics: read returns what was written (array axioms in essence)

FIFO Read / Write Order



global FIFO read / write operation gives sequential consistency (left)
projected to individual memory addresses too (right)

Store Buffer / Write Buffer



hide write latency by collecting written data and continue serving read data
(alreay in the cache or in the write buffer)

Out-of-Order Write-to-Read

```
long a, b;

void * f (void * q) {
  a = 1;
  long c = a;
  long d = b;
  long u = c + d;
  return (void*) u;
}

void * g (void * p) {
  b = 1;
  long e = b;
  long f = a;
  long v = e + f;
  return (void*) v;
}
```

```
pthread_t s, t;

int main () {
  pthread_create (&s, 0, f, 0);
  pthread_create (&t, 0, g, 0);
  long u, v;
  pthread_join (s, (void**) &u);
  pthread_join (t, (void**) &v);
  long m = u + v;
  printf ("%ld\n", m);
  return 0;
}
```

Out-of-Order Write-to-Read

```
long a, b;

long f () { a = 1; long tmp = a; return tmp + b; }
long g () { b = 1; long tmp = b; return tmp + a; }

void * f (void * q) {
  a = 1;                // fwa1 = f writes a value 1 to memory
  long c = a;           // frac = f reads  a value c from memory
  long d = b;           // frbd = f reads  b value d from memory
  long u = c + d;       // fadd = f adds   c and   d locally
  return (void*) u;
}

void * g (void * p) {
  b = 1;                // gwb1 = g writes b value 1 to memory
  long e = b;           // grbe = g reads  b value e from memory
  long f = a;           // graf = g reads  a value f from memory
  long v = e + f;       // gadd = g adds   e and   f locally
  return (void*) v;
}
```

common sequentially consistent interleaved scenario with result 3

```
long a, b;

void * f (void * q) {
  a = 1;                // fwa1
  long c = a;           // frac
  long d = b;           // frbd
  long u = c + d;       // fadd
  return (void*) u;
}

void * g (void * p) {
  b = 1;                // gwb1
  long e = b;           // grbe
  long f = a;           // graf
  long v = e + f;       // gadd
  return (void*) v;
}
```

```
abcdefuvm memory-fifo
00------- fwa1
00------- fwa1 frac frbd
10------- frac frbd
101------ frbd
1010----- gwb1
1010----- gwb1 grbe
1010----- gwb1 grbe graf
1110----- grbe graf
11101---- graf
111011--- fadd
111011--- fadd gadd
111011--- fadd gadd madd
1110111-- gadd madd
11101112- madd
111011123
```

rare sequentially consistent interleaved scenario with result 4

```
long a, b;

void * f (void * q) {
  a = 1;                // fwa1
  long c = a;           // frac
  long d = b;           // frbd
  long u = c + d;       // fadd
  return (void*) u;
}

void * g (void * p) {
  b = 1;                // gwb1
  long e = b;           // grbe
  long f = a;           // graf
  long v = e + f;       // gadd
  return (void*) v;
}
```

```
abcdefuvm memory-fifo
00------- fwa1
00------- fwa1 gwb1
00------- fwa1 gwb1 frac
00------- fwa1 gwb1 frac grbe
00------- fwa1 gwb1 frac grbe frbd
00------- fwa1 gwb1 frac grbe frbd graf
10------- gwb1 frac grbe frbd graf
11------- frac grbe frbd graf
111------ grbe frbd graf
111-1---- frbd graf
11111---- graf
111111--- fadd
111111--- fadd gadd
111111--- fadd gadd madd
1111112-- gadd madd
11111122- madd
111111224
```

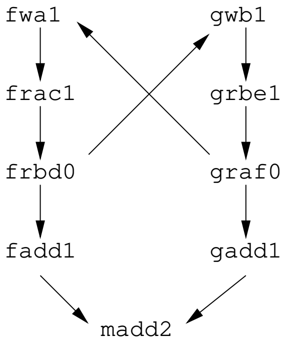
less frequent sequentially *inconsistent* scenario with result 2

```
long a, b;

void * f (void * q) {
  a = 1;              // fwa1
  long c = a;         // frac
  long d = b;         // frbd
  long u = c + d;     // fadd
  return (void*) u;
}

void * g (void * p) {
  b = 1;              // gwb1
  long e = b;         // grbe
  long f = a;         // graf
  long v = e + f;     // gadd
  return (void*) v;
}
```

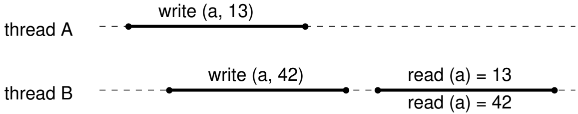
```
abcdefuvm  memory-fifo
00-------  fwa1
00-------  fwa1 frac frbd
001------  fwa1 frbd           // frac ooo
0010-----  fwa1 gwb1
0110-----  fwa1
0110-----  fwa1 grbe
01101----  fwa1 graf
011010---  fwa1
111010---  fadd
111010---  fadd gadd
111010---  fadd gadd madd
1110101--  gadd madd
11101011-  madd
111010112
```

no sequentially consistent scenario with result 2

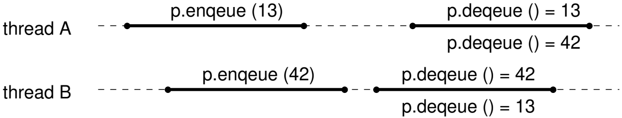
```
long a, b;

void * f (void * q) {
  a = 1;                // fwa1
  long c = a;           // frac
  long d = b;           // frbd
  long u = c + d;       // fadd
  return (void*) u;
}

void * g (void * p) {
  b = 1;                // gwb1
  long e = b;           // grbe
  long f = a;           // graf
  long v = e + f;       // gadd
  return (void*) v;
}
```



Linearizability



- consistency can be extended to method calls
  - method calls take time during a time interval: invocation to response
  - example above with read / write on memory
  - below with enqueue / dequeue on queue

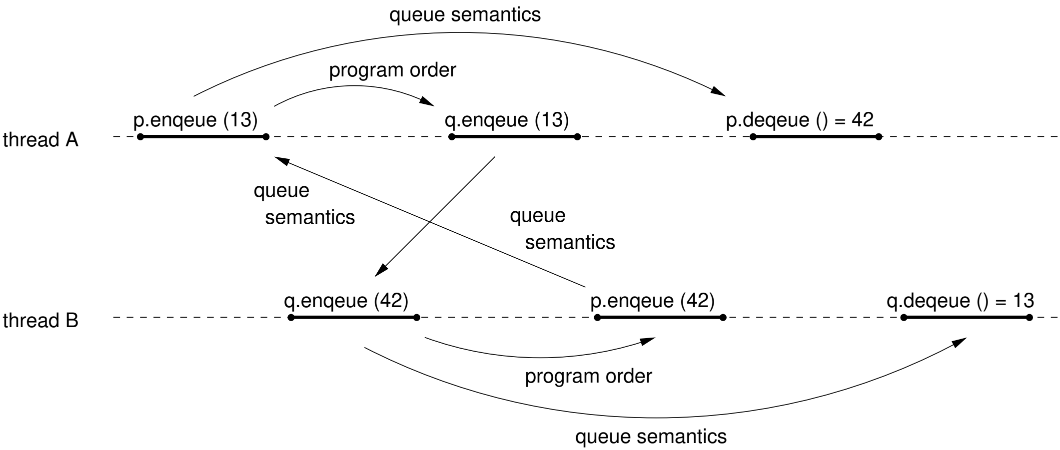


- execution **linearizable** iff

  there is a linearization point between invocation and response
  where the method appears to take effect instantaneously

- at the linearization point the effect of a method becomes visible to other threads

locally sequentially consistent but globally not (nor linearizable)



Progress Conditions: Wait-Free, Lock-Free

- a **total** method is defined in any state, otherwise **partial**
  - like "dequeue" is partial and "enqueue" (in an unbounded queue) is total
  - same for "read" and "write"
- method is **blocking** iff response can not be computed immediately
  - common scenario in multi-processor systems
- linearizable computations can always be extended with pending responses of total messages
  - so in principle pending total method responses never have to be blocking
  - but it might be dificult to compute the actual response
- method m **wait-free** iff every invocation eventually leads to a response
  - in the strong liveness sense, e.g., within a finite number of steps
  - or in LTL $\forall m[\mathsf{G}\,(m.\text{invocation} \rightarrow \mathsf{F}\,m.\text{response})]$
- method m **lock-free** iff infinitely often some method call finishes
  - so some threads might "starve", but the overall system makes progress
  - or in LTL $(\exists m[\mathsf{GF}m.\text{invocation}]) \rightarrow \mathsf{GF}\,\exists m'[m'.\text{response}]$
- every wait-free method is also lock-free
  - wait-free provides stronger correctness guarantee
  - usually minimizes "latency" and leads to less efficiency in terms of through put
  - and is harder to implement

Compare-And-Swap (CAS)

```
// GCC's builtin function for CAS

bool __sync_bool_compare_and_swap (type *ptr, type oldval, type newval);

// it atomically executes the following function

bool CAS (type * address, type expected, type update) {
  if (*address != expected) return false;
  *address = update;
  return true;
}
```

- considered the “mother” of all atomic operations
  - many modern architectures support CAS
  - alternatives: load-linked / store-conditional (LL/SC)
  - see discussion of memory model for RISC-V too
- compiler uses CAS or LL/SC to implement other atomic operations
  - if processors does not support corresponding operations
  - like atomic increment
  - C++11 atomics

Treiber Stack

Treiber, R.K..
Systems programming: Coping with parallelism.
IBM, Thomas J. Watson Research Center, 1986.

- probably first lock-free data-structure
- implements a parallel stack
- suffers from ABA problem
- see demo

Others

hazard pointers

false sharing

queues (Michael & Scott Queue)

relaxed data structures (k-stack)

Andreas Haas, Thomas Hütter, Christoph M. Kirsch, Michael Lippautz, Mario Preishuber, Ana Sokolova:
Scal: A Benchmarking Suite for Concurrent Data Structures.
NETYS 2015: 1-14

`http://scal.cs.uni-salzburg.at`

Paul E. McKenney
Is Parallel Programming Hard, And, If So, What Can You Do About It?
https://mirrors.edge.kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html