CS 33

Multithreaded Programming VII

Implementing Mutexes

- Strategy
  - make the usual case (no waiting) very fast
  - can afford to take more time for the other case (waiting for the mutex)

Futexes

- Safe, *efficient* kernel conditional queueing in Linux
- All operations performed atomically
  - `futex_wait(futex_t *futex, int val)`
    - » if `futex->val` is equal to `val`, then sleep
    - » otherwise return
  - `futex_wake(futex_t *futex)`
    - » wake up one thread from `futex`'s wait queue, if there are any waiting threads

For details on futexes, avoid the Linux man pages, but look at http://people.redhat.com/drepper/futex.pdf, from which this material was obtained. Note that there's actually just one **futex** system call; whether it's a **wait** or a **wakeup** is specified by an argument.

Ancillary Functions

- `int atomic_inc(int *val)`
  - **add 1 to `*val`, return its original value**
- `int atomic_dec(int *val)`
  - **subtract 1 from `*val`, return its original value**
- CAS:

```
int CAS(int *ptr, int old, int new) {
    int tmp = *ptr;
    if (*ptr == old)
        *ptr = new;
    return tmp;
}
```


These functions are available on most architectures, particularly on the x86. Note that their effect must be **atomic**: everything happens at once.

How can these instructions be made to be atomic? What's done is memory is accessed via special instructions that cause the memory controller to respond to a load then a store without anything happening in between. Thus, for the example of **atomic_inc**, **val** is loaded from memory, then incremented (in the processor), then stored back to memory. While this happens, no other load or stores may be done. If this were done for every instruction, memory access would slow down considerably, but doing it just occasionally has no severe effect.

Attempt 1

```
void lock(futex_t *futex) {
  int c;
  while ((c = atomic_inc(&futex->val)) != 0)
    futex_wait(futex, c+1);
}

void unlock(futex_t *futex) {
  futex->val = 0;
  futex_wake(futex);
}
```


If the futex's value is 0, it's unlocked, otherwise it's locked.

Quiz 1

```
void lock(futex_t *futex) {
  int c;
  while ((c = atomic_inc(&futex->val)) != 0)
    futex_wait(futex, c+1);
}

void unlock(futex_t *futex) {
  futex->val = 0;
  futex_wake(futex);
}
```

Why doesn't Attempt 1 work?

a) unlock fails to wake up a sleeping thread in certain circumstances
b) the while loop in lock doesn't terminate in certain circumstances
c) both of the above
d) none of the above

Attempt 2

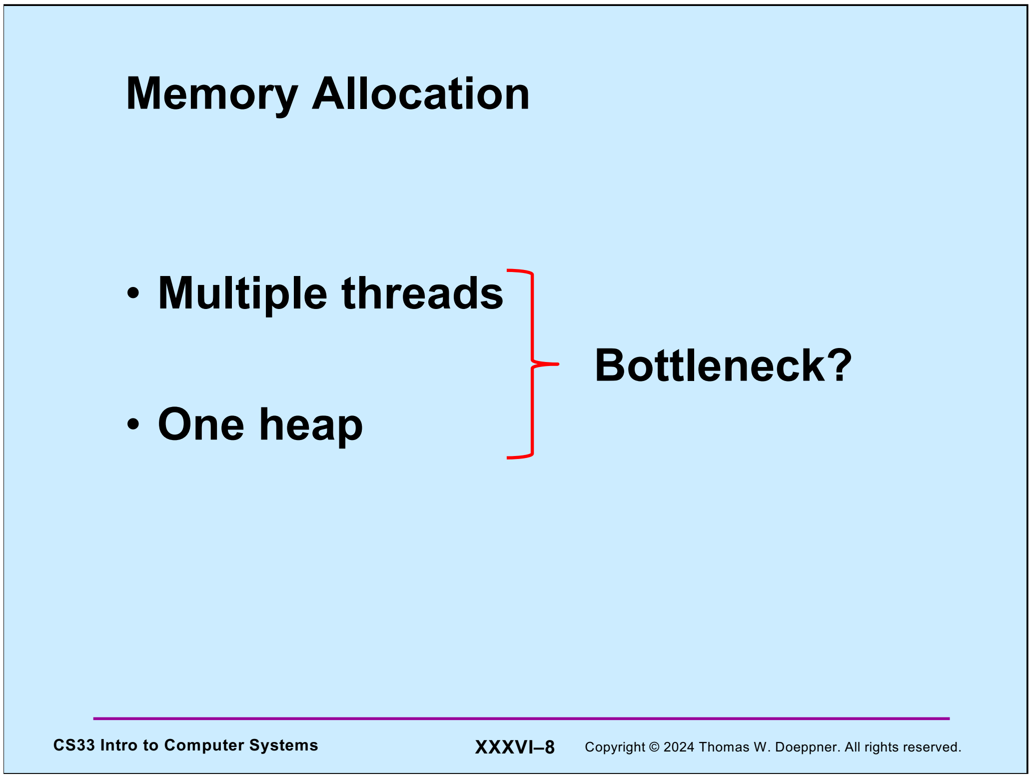
```
void lock(futex_t *futex) {
  int c;
  if ((c = CAS(&futex->val, 0, 1) != 0)
    do {
      if (c == 2 || (CAS(&futex->val, 1, 2) != 0))
        futex_wait(futex, 2);
    while ((c = CAS(&futex->val, 0, 2)) != 0))
}

void unlock(futex_t *futex) {
  if (atomic_dec(&futex->val) != 1) {
    futex->val = 0;
    futex_wake(futex);
  }
}
```

Quiz 2

Does it work?

a) always
b) except for pathological cases
c) rarely
d) never

In this version, if the futex's value is 0, it's unlocked, if it's one it's locked and no threads are waiting for it; if it's greater than one it's locked and there might be threads waiting for it.



In a naïve multithreaded implementation of malloc/free, there is one mutex protecting the heap, resulting in a bottleneck – a multithreaded program might be slowed down considerably since all threads that manipulate the heap must compete for the mutex.

Solution 0:

Use your malloc implementation but use mutexes to make it thread-safe

1) **Use a single mutex to protect the heap**
   - **no concurrent access**
2) **Use a mutex per block**
   - **concurrent access to the heap**

Quiz 3

Solution 0.2 is not used because

a) Since the free list is circular, deadlock cannot be avoided
b) Since each core accesses memory via its private L1 cache, memory blocks used by one thread cannot be safely shared with others
c) There will be too many calls to lock and unlock mutexes, slowly things down a lot
d) Since there must be a mutex per block, too much memory is wasted
e) Something else

Not a Quiz

How can it be done better?

Solution 1

- Divvy up the heap among the threads
  - each thread has its own heap
  - no mutexes required
  - no bottleneck
- How much heap does each thread get?
- What if one thread frees memory malloc'd by another?

Solution 2

- Multiple "arenas"
  - each with its own mutex
  - thread allocates from the first one it can find whose mutex was unlocked
    - if none, then creates new one
  - deallocations go back to original arena

Solution 3

- Global heap plus per-thread heaps
  - threads pull storage from global heap only when needed
  - freed storage goes to per-thread heap
    - » unless things are imbalanced
      - then thread moves storage back to global heap
  - mutex on only the global heap
- What if one thread frees memory malloc'd by another?

For the latter case, the freed block goes back to the global list.

Malloc/Free Implementations

- ptmalloc
  - based on solution 2
  - in glibc (i.e., used by default)
- tcmalloc
  - based on solution 3
  - from Google
- Which is best?

Test Program

```
const unsigned int N=64, nthreads=32, iters=10000000;
int main() {
  void *tfunc(void *);
  pthread_t thread[nthreads];
  for (int i=0; i<nthreads; i++) {
    pthread_create(&thread[i], 0, tfunc, (void *)i);
    pthread_detach(thread[i]);
  }
  pthread_exit(0);
}
void *tfunc(void *arg) {
  long i;
  for (i=0; i<iters; i++) {
    long *p = (long *)malloc(sizeof(long)*((i%N)+1));
    free(p);
  }
  return 0;
}
```


In this test program, each thread does a sequence of mallocs and frees.

Not a Quiz

Which is fastest?

a) glibc (i.e., standard Linux)
b) Google

Compiling It …

```
% gcc -o ptalloc alloc.c –lpthread
% gcc -o tcalloc alloc.c –lpthread -ltcmalloc
```

Running It (2014) …

```
$ time ./ptalloc
real    0m5.142s
user    0m20.501s
sys     0m0.024s
$ time ./tcalloc
real    0m1.889s
user    0m7.492s
sys     0m0.008s
```


The code was run on an Intel(R) Core(TM)2 Quad CPU Q6600 @ 2.40GHz (4 cores).

The rows labelled **user** show the sums of the amount of time each thread spent running in user mode. The rows labelled **sys** show the sums of the amount of time each thread spent running in kernel mode. The rows labelled **real** show the time that elapsed from when the command started to when it ended. It's less than the sum of the **user** and **sys** times because multiple cores were employed: for example, if two threads running simultaneously (on different cores) each used 1 second of user time, the total user time is 2 seconds, but the real time is one second.

Running It (2024) …

```
$ time ./ptalloc
real    0m0.558s
user    0m6.141s
sys     0m0.020s
$ time ./tcalloc
real    0m0.400s
user    0m4.458s
sys     0m0.008s
```


This was run on a 2023 CS department computer: AMD Ryzen 5 3600 @ 7.20GHz (6 cores). There were 4 times as many iterations as was done in 2014.

What's Going On (2014)?

```
$ strace -c -f ./ptalloc
 …
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
100.00    0.040002          13      3007       520 futex
 …


$ strace -c -f ./tcalloc
 …
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 …
  0.00    0.000000           0        59        13 futex
 …
```


strace is a system facility that supplies information about the system calls a process uses. The –c flag tells it to print the cumulative statistics after the process terminates. The –f flag tells it to include information on all threads and child processes.

Note that the times reported are the total times taken by all threads and don't account for concurrency: i.e., two threads might each take two seconds, totalling to 4 seconds, but the real time used is just two seconds. What's signficant are the counts: the number of calls and the number of errors. Thus it's clear that ptalloc makes significantly more calls to futex than does tcalloc. Errors indicates the number of times that futex_wait returned because its second argument (val) was not equal to futex->val.

What’s Going On (2024)?

```
$ strace -c -f ./ptalloc
 …
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 …
 0.00    0.000000           0         1           futex
 …


$ strace -c -f ./tcalloc
 …
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 …
  0.38    0.000016           1        10           futex
 …
```

Test Program 2, part 1

```
#define N 64
#define npairs 16
#define allocsPerIter 1024
const long iters = 8*1024*1024/allocsPerIter;
#define BufSize 10240
typedef struct buffer {
  int *buf[BufSize];
  unsigned int nextin;
  unsigned int nextout;
  sem_t empty;
  sem_t occupied;
  pthread_t pthread;
  pthread_t cthread;
} buffer_t;
```


This program creates pairs of threads: one thread allocates storage, the other deallocates storage. They communicate using producer-consumer communication.

Test Program 2, part 2

```
int main() {
  long i;
  buffer_t b[npairs];
  for (i=0; i<npairs; i++) {
    b[i].nextin = 0;
    b[i].nextout = 0;
    sem_init(&b[i].empty, 0, BufSize/allocsPerIter);
    sem_init(&b[i].occupied, 0, 0);
    pthread_create(&b[i].pthread, 0, prod, &b[i]);
    pthread_create(&b[i].cthread, 0, cons, &b[i]);
  }
  for (i=0; i<npairs; i++) {
    pthread_join(b[i].pthread, 0);
    pthread_join(b[i].cthread, 0);
  }
  return 0;
}
```


The main function creates **npairs** (16) of communicating pairs of threads.

Test Program 2, part 3

```
void *prod(void *arg) {
  long i, j;
  buffer_t *b = (buffer_t *)arg;
  for (i = 0; i<iters; i++) {
    sem_wait(&b->empty);
    for (j = 0; j<allocsPerIter; j++) {
      b->buf[b->nextin] = malloc(sizeof(int)*((j%N)+1));
      if (++b->nextin >= BufSize)
        b->nextin = 0;
    }
    sem_post(&b->occupied);
  }
  return 0;
}
```


To reduce the number of calls to **sem_wait** and **sem_post**, at each iteration the thread calls malloc **allocsPerIter** (1024) times.

Test Program 2, part 4

```
void *cons(void *arg) {
  long i, j;
  buffer_t *b = (buffer_t *)arg;
  for (i = 0; i<iters; i++) {
    sem_wait(&b->occupied);
    for (j = 0; j<allocsPerIter; j++) {
      free(b->buf[b->nextout]);
      if (++b->nextout >= BufSize)
        b->nextout = 0;
    }
    sem_post(&b->empty);
  }
  return 0;
}
```


Running It (2014) …

```
$ time ./ptalloc2
real    0m1.087s
user    0m3.744s
sys     0m0.204s
$ time ./tcalloc2
real    0m3.535s
user    0m11.361s
sys     0m2.112s
```


The code was run on a SunLab machine (an Intel(R) Core(TM)2 Quad CPU Q6600 @ 2.40GHz).

Running It (2024) …

```
$ time ./ptalloc2
real    0m1.594s
user    0m8.778s
sys     0m2.551s
$ time ./tcalloc2
real    0m7.089s
user    0m59.871s
sys     0m11.220s
```


This was run on a 2024 CS department computer: AMD Ryzen 5 3600 @ 7.20GHz (6 cores).

What's Going On (2014)?

```
$ strace -c -f ./ptalloc2
 …
% time     seconds  usecs/call     calls    errors syscall
 …
------ ----------- ----------- --------- --------- ----------------
 …
 93.04    8.246196         117     70173     20775 futex
…
$ strace -c -f ./tcalloc2
 …
% time     seconds  usecs/call     calls    errors syscall
 …
------ ----------- ----------- --------- --------- ----------------
99.92   47.796676          153    311012      7244 futex
 …
```


What's Going On (2024)?

```
$ strace -c -f ./ptalloc2
 …
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 98.55   55.917331         138    403494    108889 futex
…
$ strace -c -f ./tcalloc2
 …
% time     seconds  usecs/call     calls    errors syscall
------ ----------- ----------- --------- --------- ----------------
 99.98  298.581838         149   2002633     22522 futex
 …
```