15-213

"The course that gives CMU its Zip!"

Concurrency II: Synchronization
Nov 14, 2000

Topics

- Progress graphs
- Semaphores
- Mutex and condition variables
- Barrier synchronization
- Timeout waiting

A version of `badcnt.c` with a simple counter loop

```
int ctr = 0; /* shared */

/* main routine creates*/
/* two count threads */

/* count thread */
void *count(void *arg) {
  int i;

  for (i=0; i<NITERS; i++)
    ctr++;
  return NULL;
}
```

note: counter should be equal to 200,000,000

```
linux> badcnt
BOOM! ctr=198841183

linux> badcnt
BOOM! ctr=198261801

linux> badcnt
BOOM! ctr=198269672
```

What went wrong?

Assembly code for counter loop

C code for counter loop

```
for (i=0; i<NITERS; i++)
    ctr++;
```

Corresponding asm code (gcc -O0 -fforce-mem)

Head (H_i)

```
.L9:
        movl -4(%ebp),%eax
        cmpl $99999999,%eax
        jle .L12
        jmp .L10
```

Load ctr (L_i)
Update ctr (U_i)
Store ctr (S_i)

```
.L12:
        movl ctr,%eax    # Load
        leal 1(%eax),%edx   # Update
        movl %edx,ctr    # Store
```

Tail (T_i)

```
.L11:
        movl -4(%ebp),%eax
        leal 1(%eax),%edx
        movl %edx,-4(%ebp)
        jmp .L9
.L10:
```


Concurrent execution

Key thread idea: In general, any sequentially consistent interleaving is possible, but some are incorrect!

- I_i denotes that thread i executes instruction I
- $\%eax_i$ is the contents of %eax in thread i's context

i (thread)	$instr_i$	$\%eax_1$	$\%eax_2$	ctr
1	H_1	-	-	0
1	L_1	0	-	0
1	U_1	1	-	0
1	S_1	1	-	1
2	H_2	-	-	1
2	L_2	-	1	1
2	U_2	-	2	1
2	S_2	-	2	2
2	T_2	-	2	2
1	T_1	1	-	2

OK

Concurrent execution (cont)

Incorrect ordering: two threads increment the counter, but the result is 1 instead of 2.

i (thread)	$instr_i$	$\%eax_1$	$\%eax_2$	ctr
1	H_1	-	-	0
1	L_1	0	-	0
1	U_1	1	-	0
2	H_2	-	-	0
2	L_2	-	0	0
1	S_1	1	-	1
1	T_1	1	-	1
2	U_2	-	1	1
2	S_2	-	1	1
2	T_2	-	1	1

Oops!

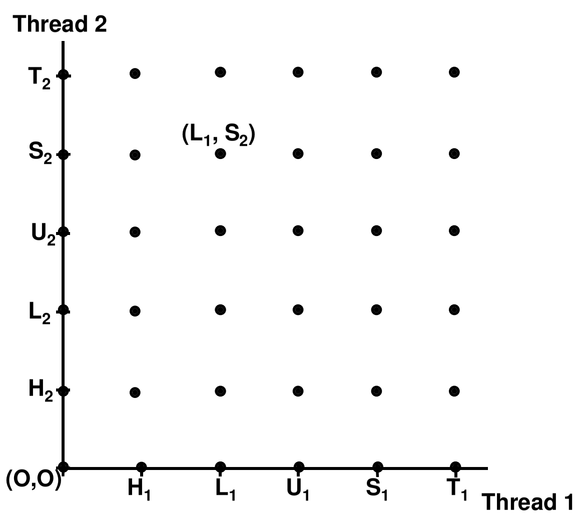
Concurrent execution (cont)

How about this ordering?

i (thread)	$instr_i$	$\%eax_1$	$\%eax_2$	ctr
1	H_1			
1	L_1			
2	H_2			
2	L_2			
2	U_2			
2	S_2			
1	U_1			
1	S_1			
1	T_1			
2	T_2			

We can clarify our understanding of concurrent execution with the help of the *progress graph*

Progress graphs



A *progress graph* depicts the discrete *execution state space* of concurrent threads.

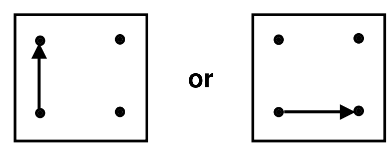
Each axis corresponds to the sequential order of instructions in a thread.

Each point corresponds to a possible *execution state* ($Inst_1$, $Inst_2$).

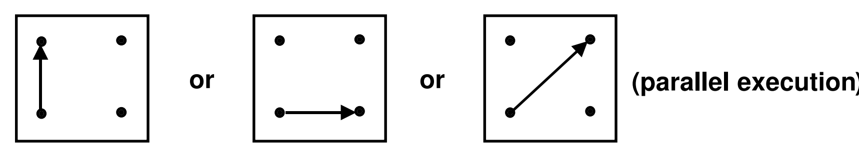
E.g., (L_1, S_2) denotes state where thread 1 has completed L_1 and thread 2 has completed S_2.

Legal state transitions

Interleaved concurrent execution (one processor):

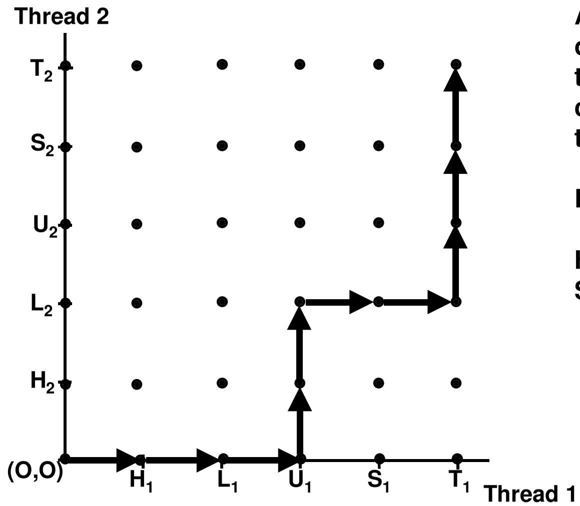


Parallel concurrent execution (multiple processors)



Key point: Always reason about concurrent threads as if each thread had its own CPU.

Trajectories

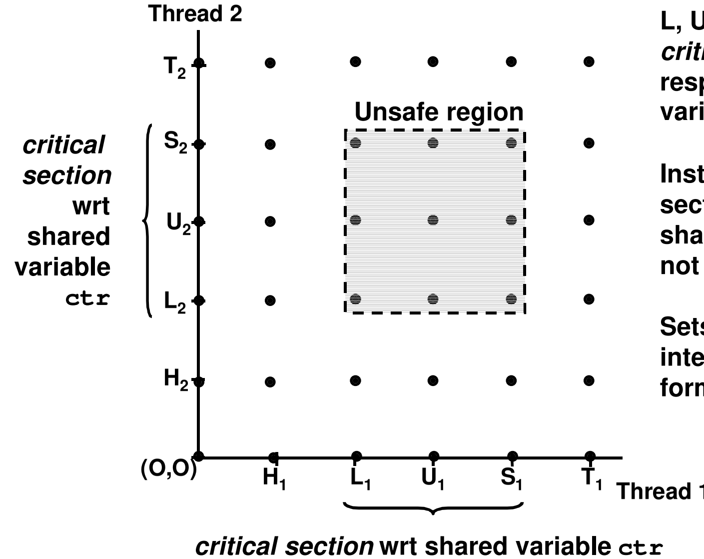


A *trajectory* is a sequence of legal state transitions that describes one possible concurrent execution of the threads.

Example:

H1, L2, U1, H2, L2, S1, T1, U2, S2, T2

Critical sections and unsafe regions

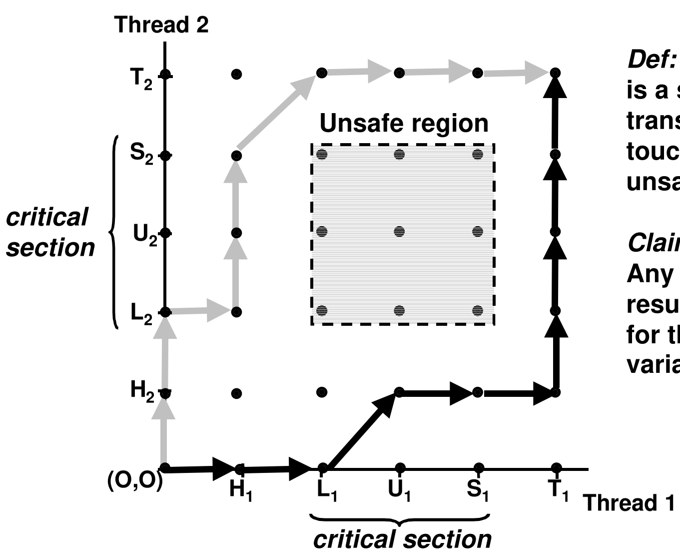


L, U, and S form a *critical section* with respect to the shared variable `ctr`.

Instructions in critical sections (wrt to some shared variable) should not be interleaved.

Sets of states where such interleaving occurs form *unsafe regions*.

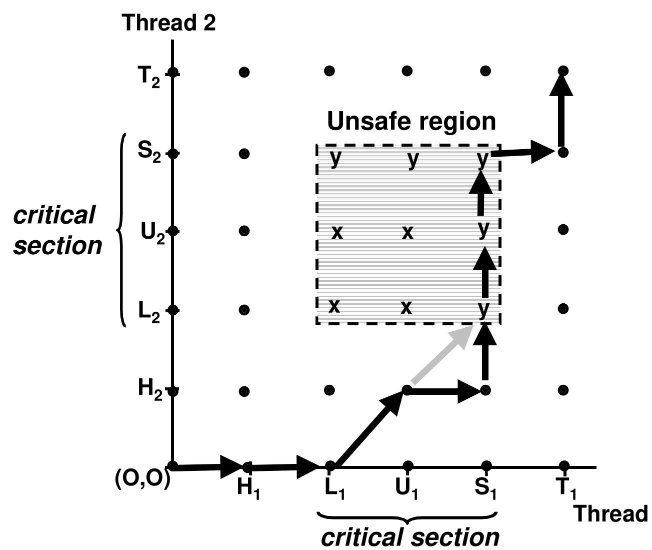
Safe trajectories



Def: A *safe trajectory* is a sequence of legal transitions that does not touch any states in an unsafe region.

Claim:
Any safe trajectory results in a correct value for the shared variable `ctr`.

Unsafe trajectories



Touching a state of type x is always incorrect.

Touching a state of type y may or may not be OK:

- correct because store completes before load.
- incorrect because order of load and store are indeterminate.

Moral: be conservative and disallow all unsafe trajectories.

Semaphore operations

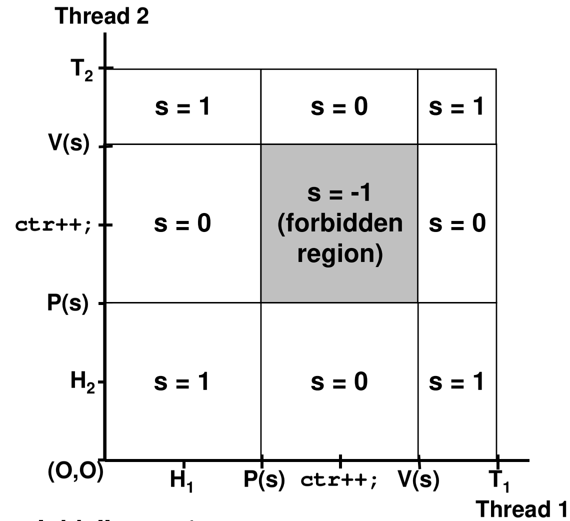
Question: **How can we guarantee a safe trajectory?**

- **We must *synchronize* the threads so that they never enter an unsafe state.**

Classic solution*: Dijkstra's P and V operations on *semaphores.

- ***semaphore:* non-negative integer synchronization variable.**
- **P(s): [`while (s == 0) wait(); s--;`]**
  - Dutch for "Proberen" (test)
- **V(s): [`s++;`]**
  - Dutch for "Verhogen" (increment)
- **OS guarantees that operations between brackets [ ] are executed indivisibly.**
  - **Only one P or V operation at a time can modify s.**
  - **When while loop in P terminates, only that P can decrement s.**
- **Semaphore invariant: *(s >= 0)***

Sharing with semaphores



Initially, s = 1

Provide mutually exclusive access to shared variable by surrounding critical section with P and V operations on semaphore `s` (initially set to 1).

Semaphore invariant creates a *forbidden region* that encloses unsafe region and is never touched by any trajectory.

Semaphore used in this way is often called a *mutex* (mutual exclusion).

Posix semaphores

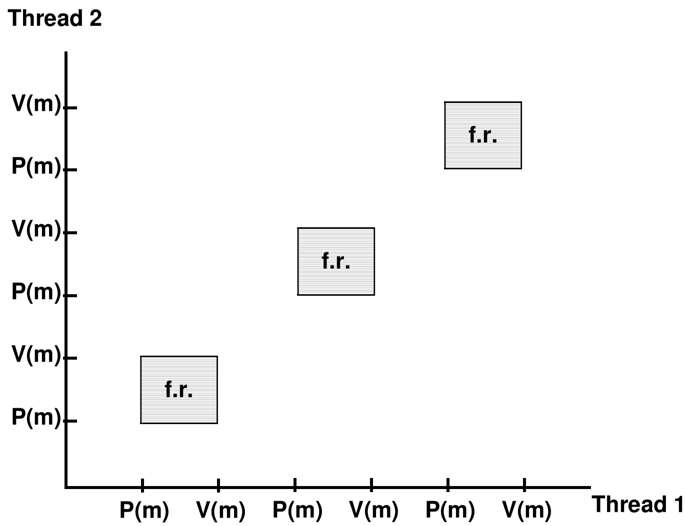
```
/* initialize semaphore sem to value */
/* pshared=0 if thread, pshared=1 if process */
void Sem_init(sem_t *sem, int pshared, unsigned int value) {
  if (sem_init(sem, pshared, value) < 0)
    unix_error("Sem_init");
}

/* P operation on semaphore sem */
void P(sem_t *sem) {
  if (sem_wait(sem))
    unix_error("P");
}

/* V operation on semaphore sem */
void V(sem_t *sem) {
  if (sem_post(sem))
    unix_error("V");
}
```


Sharing with Posix semaphores

```
/* goodcnt.c - properly synch'd */
/* version of badcnt.c */
#include <ics.h>
#define NITERS 10000000

void *count(void *arg);

struct {
  int ctr;     /* shared ctr */
  sem_t mutex; /* semaphore */
} shared;

int main() {
  pthread_t tid1, tid2;

  /* init mutex semaphore to 1 */
  Sem_init(&shared.mutex, 0, 1);

  /* create 2 ctr threads and wait */
  ...
}
```

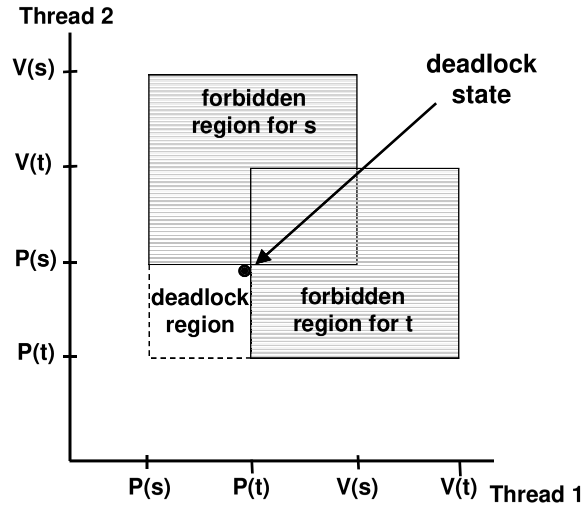
```
/* counter thread */
void *count(void *arg) {
  int i;

  for (i=0; i<NITERS; i++) {
    P(&shared.mutex);
    shared.ctr++;
    V(&shared.mutex);
  }
  return NULL;
}
```

Progress graph for `goodcnt.c`



Initially, mutex = 1

Deadlock



Initially, s=t=1

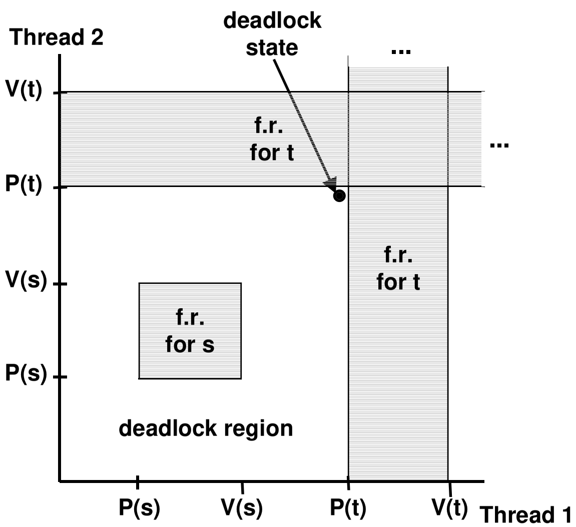
Semaphores introduce the potential for *deadlock:* waiting for a condition that will never be true.

Any trajectory that enters the *deadlock region* will eventually reach the *deadlock state*, waiting for either `s` or `t` to become nonzero.

Other trajectories luck out and skirt the deadlock region.

Unfortunate fact: deadlock is often non-deterministic.

A deterministic deadlock



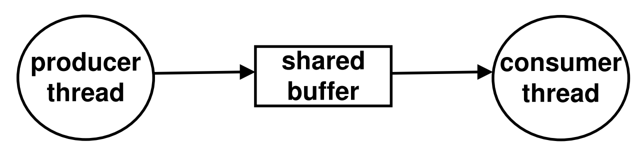
Initially, s = 1, t = 0.

Sometimes though, we get "lucky" and the deadlock is deterministic.

Here is an example of a deterministic deadlock caused by improperly initializing semaphore t.

Problem: correct this program and draw the resulting forbidden regions.

Signaling with semaphores



Common synchronization pattern:

- Producer waits for slot, inserts item in buffer, and signals consumer.
- Consumer waits for item, removes it from buffer, and signals producer.

Examples

- Multimedia processing:
  - producer creates MPEG video frames, consumer renders the frames
- Graphical user interfaces
  - producer detects mouse clicks, mouse movements, and keyboard hits and inserts corresponding events in buffer.
  - consumer retrieves events from buffer and paints the display.

Producer-consumer (1-buffer)

```
/* buf1.c - producer-consumer
on 1-element buffer */
#include <ics.h>

#define NITERS 5

void *producer(void *arg);
void *consumer(void *arg);

struct {
  int buf; /* shared var */
  sem_t full; /* sems */
  sem_t empty;
} shared;
```

```
int main() {
  pthread_t tid_producer;
  pthread_t tid_consumer;

  /* initialize the semaphores */
  Sem_init(&shared.empty, 0, 1);
  Sem_init(&shared.full,  0, 0);

  /* create threads and wait */
  Pthread_create(&tid_producer, NULL,
                 producer, NULL);
  Pthread_create(&tid_consumer, NULL,
                 consumer, NULL);
  Pthread_join(tid_producer, NULL);
  Pthread_join(tid_consumer, NULL);

  exit(0);
}
```

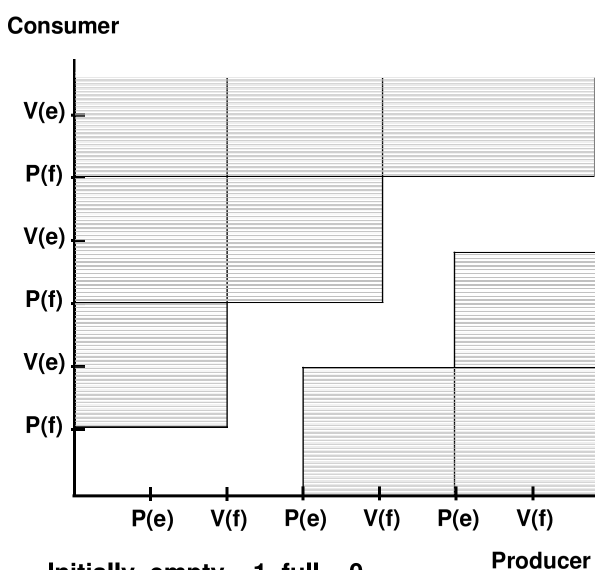

Producer-consumer (cont)

Initially: empty = 1, full = 0.

```
/* producer thread */
void *producer(void *arg) {
  int i, item;

  for (i=0; i<NITERS; i++) {
    /* produce item */
    item = i;
    printf("produced %d\n",
           item);

    /* write item to buf */
    P(&shared.empty);
    shared.buf = item;
    V(&shared.full);
  }
  return NULL;
}
```

```
/* consumer thread */
void *consumer(void *arg) {
  int i, item;

  for (i=0; i<NITERS; i++) {
    /* read item from buf */
    P(&shared.full);
    item = shared.buf;
    V(&shared.empty);

    /* consume item */
    printf("consumed %d\n",
           item);
  }
  return NULL;
}
```


Producer-consumer progress graph



Initially, empty = 1, full = 0.

The forbidden regions prevent the producer from writing into a full buffer.

They also prevent the consumer from reading an empty buffer.

***Problem:* Write version for n-element buffer with multiple producers and consumers.**

Limitations of semaphores

Semaphores are sound and fundamental, but they have limitations.

- **Difficult to broadcast a signal to a group of threads.**
  - e.g., *barrier synchronization:* no thread returns from the barrier function until every other thread has called the barrier function.
- **Impossible to do timeout waiting.**
  - e.g., wait for at most 1 second for a condition to become true.

For these we must use Pthreads mutex and condition variables.

Basic operations on mutex variables

```
int pthread_mutex_init(pthread_mutex_t *mutex,
                       pthread_mutexattr_t *attr)
```

Initializes a mutex variable (`mutex`) with some attributes (`attr`).

- attributes are usually NULL.
- like initializing a mutex semaphore to 1.

```
int pthread_mutex_lock(pthread_mutex_t *mutex)
```

Indivisibly waits for `mutex` to be unlocked and then locks it.

- like `P(mutex)`

```
int pthread_mutex_unlock(pthread_mutex_t *mutex)
```

Unlocks `mutex`.

- like `V(mutex)`

Basic operations on condition variables

```
int pthread_cond_init(pthread_cond_t *cond,
                      pthread_condattr_t *attr)
```

Initializes a condition variable (`cond`) with some attributes (`attr`).

- attributes are usually NULL.

```
int pthread_cond_signal(pthread_cond_t *cond)
```

Awakens one thread waiting on condition `cond`.

- if no threads waiting on condition, then it does nothing.
- key point: signals are not queued!

```
int pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex)
```

Indivisibly unlocks `mutex` and waits for signal on condition `cond`

- When awakened, indivisibly locks `mutex`.

Advanced operations on condition variables

```
int pthread_cond_broadcast(pthread_cond_t *cond)
```

Awakens *all* threads waiting on condition `cond`.

- if no threads waiting on condition, then it does nothing.

```
int pthread_cond_timedwait(pthread_cond_t *cond,
                           pthread_mutex_t *mutex,
                           struct timespec *abstime)
```

Waits for condition `cond` until absolute wall clock time is `abstime`

- Unlocks `mutex` on entry, locks `mutex` on awakening.
- Use of absolute time rather than relative time is strange.

Signaling and waiting on conditions

Basic pattern for signaling

```
Pthread_mutex_lock(&mutex);
Pthread_cond_signal(&cond);
Pthread_mutex_unlock(&mutex);
```

Basic pattern for waiting

```
Pthread_mutex_lock(&mutex);
Pthread_cond_wait(&cond, &mutex);
Pthread_mutex_unlock(&mutex);
```

A mutex is always associated with a condition variable.

Guarantees that the condition cannot be signaled (and thus ignored) in the interval when the waiter locks the mutex and waits on the condition.

Barrier synchronization

```
#include <ics.h>

static pthread_mutex_t mutex;
static pthread_cond_t cond;
static int nthreads;
static int barriercnt = 0;

void barrier_init(int n) {
  nthreads = n;
  Pthread_mutex_init(&mutex, NULL);
  Pthread_cond_init(&cond, NULL);
}

void barrier() {
  Pthread_mutex_lock(&mutex);
  if (++barriercnt == nthreads) {
    barriercnt = 0;
    Pthread_cond_broadcast(&cond);
  }
  else
    Pthread_cond_wait(&cond, &mutex);
  Pthread_mutex_unlock(&mutex);
}
```

Call to `barrier` will not return until every other thread has also called `barrier`.

Needed for tightly-coupled parallel applications that proceed in phases. E.g., physical simulations.

timebomb.c: timeout waiting example

A program that explodes unless the user hits a key within 5 seconds.

```
#include <ics.h>
#define TIMEOUT 5

/* function prototypes */
void *thread(void *vargp);
struct timespec *maketimeout(int secs);

/* condition variable and
its associated mutex */
pthread_cond_t cond;
pthread_mutex_t mutex;

/* thread id */
pthread_t tid;
```


timebomb.c (cont)

A routine for building a timeout structure for `pthread_cond_timewait`.

```
/*
 * maketimeout - builds a timeout object that times out
 *               in secs seconds
 */
struct timespec *maketimeout(int secs) {
  struct timeval now;
  struct timespec *tp =
         (struct timespec *)malloc(sizeof(struct timespec));

  gettimeofday(&now, NULL);
  tp->tv_sec = now.tv_sec + secs;
  tp->tv_nsec = now.tv_usec * 1000;
  return tp;
}
```


Main routine for timebomb.c

```
int main() {
  int i, rc;

  /* initialize the mutex and condition variable */
  Pthread_cond_init(&cond, NULL);
  Pthread_mutex_init(&mutex, NULL);

  /* start getchar thread and wait for it to timeout */
  Pthread_mutex_lock(&mutex);
  Pthread_create(&tid, NULL, thread, NULL);
  for (i=0; i<TIMEOUT; i++) {
    printf("BEEP\n");
    rc = pthread_cond_timedwait(&cond, &mutex, maketimeout(1));
    if (rc != ETIMEDOUT) {
      printf("WHEW!\n");
      exit(0);
    }
  }
  printf("BOOM!\n");
  exit(0);
}
```

Thread routine for timebomb.c

```
/*
 * thread - executes getchar in a separate thread
 */
void *thread(void *vargp) {

  (void) getchar();

  Pthread_mutex_lock(&mutex);
  Pthread_cond_signal(&cond);
  Pthread_mutex_unlock(&mutex);
  return NULL;
}
```


Threads summary

Threads provide another mechanism for writing concurrent programs.

Threads are growing in popularity

- Somewhat cheaper than processes.
- Easy to share data between threads.

However, the ease of sharing has a cost:

- Easy to introduce subtle synchronization errors.

For more info:

- man pages (`man -k pthreads`)
- D. Butenhof, "Programming with Posix Threads", Addison-Wesley, 1997.