Concurrency: Condition Variables, PCP, 5DP

CS 571: Operating Systems (Spring 2021)

Lecture 8

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Some material taken/derived from:
- Wisconsin CS-537 materials created by Remzi Arpaci-Dusseau.

Go programming tutorial is out

- The tutorial includes:
  - a pre-recorded video created by Michael
  - a slide deck
  - handout1 (basic syntax)
  - handout2 (Go exercises) – solution will be posted in Week 12

- Goal is to familiarize yourself about Go programming (in addition to Project 0b)

Condition Variables

Condition Variables

A parent waiting for its child

```
void *child(void *arg) {
    printf("child\n");
    // XXX how to indicate we are done?
    return NULL;
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // create child
    // XXX how to wait for child?
    printf("parent: end\n");
    return 0;
}
```

Spin-based Approach

Using a shared variable, parent spins until child set it to 1

```
volatile int done = 0;

void *child(void *arg) {
    printf("child\n");
    done = 1;
    return NULL;
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // create child
    while (done == 0)
        ; // spin
    printf("parent: end\n");
    return 0;
}
```

Spin-based Approach

Using a shared variable, parent spins until child set it to 1

```
volatile int done = 0;

void *child(void *arg) {
    printf("child\n");
    done = 1;
    return NULL;
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // create child
    while (done == 0)
        ; // spin
    printf("parent: end\n");
    return 0;
}
```

What's the problem of this approach?

Condition Variables (CV)

- Definition:
  - An explicit queue that threads can put themselves when some condition is not as desired (by waiting on the condition)
  - Other thread can wake one of those waiting threads to allow them to continue (by signaling on the condition)
- Pthread CV

```
pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m);
pthread_cond_signal(pthread_cond_t *c);
```

CV-based Approach

```
void *child(void *arg) {
    printf("child\n");
    thr_exit();          ??
    return NULL;
}
```

```
int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t p;
    Pthread_create(&p, NULL, child, NULL);
    thr_join();          ??
    printf("parent: end\n");
    return 0;
}
```

Broken Implementation 1

```c
void *child(void *arg) {
    printf("child\n");
    thr_exit();
    return NULL;
}
```

```c
void thr_exit() {
    Pthread_mutex_lock(&m);
    Pthread_cond_signal(&c);
    Pthread_mutex_unlock(&m);
}

void thr_join() {
    Pthread_mutex_lock(&m);
    Pthread_cond_wait(&c, &m);
    Pthread_mutex_unlock(&m);
}
```

```c
int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t p;
    Pthread_create(&p, NULL, child, NULL);
    thr_join();
    printf("parent: end\n");
    return 0;
}
```

Broken Implementation 1

```
void *child(void *arg) {
    printf("child\n");
    thr_exit();
    return NULL;
}
```

```
void thr_exit() {
    Pthread_mutex_lock(&m);
    Pthread_cond_signal(&c);
    Pthread_mutex_unlock(&m);
}

void thr_join() {
    Pthread_mutex_lock(&m);
    Pthread_cond_wait(&c, &m);
    Pthread_mutex_unlock(&m);
}
```

```
int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t p;
    Pthread_create(&p, NULL, child, NULL);
    thr_join();
    printf("parent: end\n");
    return 0;
}
```

If parent comes after child, parent sleeps forever

Broken Implementation 1

```
void thread_exit() {
        Mutex_lock(&m);           // a
        Cond_signal(&c);          // b
        Mutex_unlock(&m);         // c
}
```

```
void thread_join() {
        Mutex_lock(&m);           // x
        Cond_wait(&c, &m);        // y
        Mutex_unlock(&m);         // z
}
```

Broken Implementation 1

Parent: x y z

Child: a b c

```
void thread_exit() {
      Mutex_lock(&m);           // a
      Cond_signal(&c);          // b
      Mutex_unlock(&m);         // c
}
```

```
void thread_join() {
      Mutex_lock(&m);           // x
      Cond_wait(&c, &m);        // y
      Mutex_unlock(&m);         // z
}
```

Broken Implementation 1

Parent: x y z

Child: a b c

GOOD!

```
void thread_exit() {
      Mutex_lock(&m);          // a
      Cond_signal(&c);         // b
      Mutex_unlock(&m);        // c
}
```

```
void thread_join() {
      Mutex_lock(&m);          // x
      Cond_wait(&c, &m);       // y
      Mutex_unlock(&m);        // z
}
```

Broken Implementation 1

```
void thread_exit() {
      Mutex_lock(&m);           // a
      Cond_signal(&c);          // b
      Mutex_unlock(&m);         // c
}
```

```
void thread_join() {
      Mutex_lock(&m);           // x
      Cond_wait(&c, &m);        // y
      Mutex_unlock(&m);         // z
}
```

Broken Implementation 1

Parent: x y

Child: a b c

```
void thread_exit() {
      Mutex_lock(&m);          // a
      Cond_signal(&c);         // b
      Mutex_unlock(&m);        // c
}
```

```
void thread_join() {
      Mutex_lock(&m);          // x
      Cond_wait(&c, &m);       // y
      Mutex_unlock(&m);        // z
}
```

Broken Implementation 1

Parent: x y … ***sleeeeeeeeeep forever*** …

Child: a b c

```
void thread_exit() {
        Mutex_lock(&m);          // a
        Cond_signal(&c);         // b
        Mutex_unlock(&m);        // c
}
```

```
void thread_join() {
        Mutex_lock(&m);          // x
        Cond_wait(&c, &m);       // y
        Mutex_unlock(&m);        // z
}
```

Broken Implementation 2

```
void *child(void *arg) {
    printf("child\n");
    thr_exit();
    return NULL;
}
```

```
void thr_exit() {
    done = 1;
    Pthread_cond_signal(&c);
}

void thr_join() {
    if (done == 0)
        Pthread_cond_wait(&c);
}
```

```
int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t p;
    Pthread_create(&p, NULL, child, NULL);
    thr_join();
    printf("parent: end\n");
    return 0;
}
```

Broken Implementation 2

```
void *child(void *arg) {
    printf("child\n");
    thr_exit();
    return NULL;
}
```

```
void thr_exit() {
    done = 1;
    Pthread_cond_signal(&c);
}

void thr_join() {
    if (done == 0)
        Pthread_cond_wait(&c);
}
```

```
int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t p;
    Pthread_create(&p, NULL, child, NULL);
    thr_join();
    printf("parent: end\n");
    return 0;
}
```

No mutual exclusion, hence child may signal before parent calls `cond_wait()`. In this case, parent sleeps forever!

Broken Implementation 2

```
void thread_exit() {
        done = 1;                      // a
        Cond_signal(&c);               // b
}
```

```
void thread_join() {
        Mutex_lock(&m);                // w
        if (done == 0)                 // x
                Cond_wait(&c, &m);     // y
        Mutex_unlock(&m);              // z
}
```

Broken Implementation 2

Parent: w x y

Child: a b

```
void thread_exit() {
        done = 1;                        // a
        Cond_signal(&c);                 // b
}
```

```
void thread_join() {
        Mutex_lock(&m);                  // w
        if (done == 0)                   // x
                Cond_wait(&c, &m);       // y
        Mutex_unlock(&m);                // z
}
```

Broken Implementation 2

Parent: w x y … ***sleeeeeeeeep forever*** …

Child: a b

```
void thread_exit() {
        done = 1;                    // a
        Cond_signal(&c);             // b
}
```

```
void thread_join() {
        Mutex_lock(&m);              // w
        if (done == 0)               // x
                Cond_wait(&c, &m);   // y
        Mutex_unlock(&m);            // z
}
```

Broken Implementation 2

Parent: w x y … ***sleeeeeeeeep forever*** …

Child: a b

```
void thread_exit() {
        done = 1;                      // a
        Cond_signal(&c);               // b
}
```

```
void thread_join() {
        Mutex_lock(&m);               // w
        if (done == 0)                // x
                Cond_wait(&c, &m);    // y
        Mutex_unlock(&m);             // z
}
```

How to fix?

Broken Implementation 2

Parent: w x y … ***sleeeeeeeeep forever*** …

Child: a b

Mutex_lock(&m);

```
void thread_exit() {
        done = 1;                  // a
        Cond_signal(&c);           // b
}
```

Mutex_unlock(&m);

```
void thread_join() {
        Mutex_lock(&m);                  // w
while   ~~if~~ (done == 0)               // x
                Cond_wait(&c, &m);       // y
        Mutex_unlock(&m);                // z
}
```

Trap 1 When Using CV

Trap 1 When Using CV

Trap 1 When Using CV

Trap 1 When Using CV

Only one thread gets a signal

Trap 2 When Using CV

Condition Variable

Trap 2 When Using CV

Trap 2 When Using CV

Condition Variable

Trap 2 When Using CV

Trap 2 When Using CV

Trap 2 When Using CV

Signal lost if nobody waiting at that time

Guarantee

Upon signal, there has to be at least one thread waiting;
If there are threads waiting, at least one thread will wake

CV-based Parent-wait-for-child Approach

```c
int done  = 0;
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t c  = PTHREAD_COND_INITIALIZER;

void thr_exit() {
    Pthread_mutex_lock(&m);
    done = 1;
    Pthread_cond_signal(&c);
    Pthread_mutex_unlock(&m);
}

void *child(void *arg) {
    printf("child\n");
    thr_exit();
    return NULL;
}

void thr_join() {
    Pthread_mutex_lock(&m);
    while (done == 0)
        Pthread_cond_wait(&c, &m);
    Pthread_mutex_unlock(&m);
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t p;
    Pthread_create(&p, NULL, child, NULL);
    thr_join();
    printf("parent: end\n");
    return 0;
}
```

CV-based Parent-wait-for-child Approach

```c
int done  = 0;
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t c  = PTHREAD_COND_INITIALIZER;

void thr_exit() {
    Pthread_mutex_lock(&m);
    done = 1;
    Pthread_cond_signal(&c);
    Pthread_mutex_unlock(&m);
}

void *child(void *arg) {
    printf("child\n");
    thr_exit();
    return NULL;
}

void thr_join() {
    Pthread_mutex_lock(&m);
    while (done == 0)
        Pthread_cond_wait(&c, &m);
    Pthread_mutex_unlock(&m);
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t p;
    Pthread_create(&p, NULL, child, NULL);
    thr_join();
    printf("parent: end\n");
    return 0;
}
```

Good Rule of Thumb

Always do **1. wait** and **2. signal** while holding the lock

Why: To prevent lost signal

Classical Problems of Synchronization

- Producer-consumer problem
  - Semaphore version
  - CV-based version

- Readers-writers problem

- Dining-philosophers problem

CV-based Producer-Consumer Implementation 1

Single CV and if statement

```
cond_t  cond;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // p1
        if (count == 1)                        // p2
            Pthread_cond_wait(&cond, &mutex);  // p3
        put(i);                                // p4
        Pthread_cond_signal(&cond);            // p5
        Pthread_mutex_unlock(&mutex);          // p6
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // c1
        if (count == 0)                        // c2
            Pthread_cond_wait(&cond, &mutex);  // c3
        int tmp = get();                       // c4
        Pthread_cond_signal(&cond);            // c5
        Pthread_mutex_unlock(&mutex);          // c6
        printf("%d\n", tmp);
    }
}
```

```
int buffer;
int count = 0; // initially, empty

void put(int value) {
    assert(count == 0);
    count = 1;
    buffer = value;
}

int get() {
    assert(count == 1);
    count = 0;
    return buffer;
}
```

Put and Get routines

Single buffer

CV-based Producer-Consumer Implementation 1

Single CV and if statement

```
cond_t  cond;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);             // p1
        if (count == 1)                         // p2
            Pthread_cond_wait(&cond, &mutex);   // p3
        put(i);                                 // p4
        Pthread_cond_signal(&cond);             // p5
        Pthread_mutex_unlock(&mutex);           // p6
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);             // c1
        if (count == 0)                         // c2
            Pthread_cond_wait(&cond, &mutex);   // c3
        int tmp = get();                        // c4
        Pthread_cond_signal(&cond);             // c5
        Pthread_mutex_unlock(&mutex);           // c6
        printf("%d\n", tmp);
    }
}
```

```
int buffer;
int count = 0; // initially, empty

void put(int value) {
    assert(count == 0);
    count = 1;
    buffer = value;
}

int get() {
    assert(count == 1);
    count = 0;
    return buffer;
}
```

Put and Get routines

Single buffer

What's the problem of this approach?

CV-based Producer-Consumer Implementation 1

C1 running

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // c1
        if (count == 0)                       // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                      // c4
        Pthread_cond_signal(&cond);           // c5
        Pthread_mutex_unlock(&mutex);         // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // p1
        if (count == 1)                       // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                               // p4
        Pthread_cond_signal(&cond);           // p5
        Pthread_mutex_unlock(&mutex);         // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get

CV-based Producer-Consumer Implementation 1

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // c1
        if (count == 0)                        // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                       // c4
        Pthread_cond_signal(&cond);            // c5
        Pthread_mutex_unlock(&mutex);          // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // p1
        if (count == 1)                        // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                                // p4
        Pthread_cond_signal(&cond);            // p5
        Pthread_mutex_unlock(&mutex);          // p6
    }
}
```

P running

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep		Ready	p1	Running	0	
	Sleep		Ready	p2	Running	0	

CV-based Producer-Consumer Implementation 1

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);              // c1
        if (count == 0)                          // c2
            Pthread_cond_wait(&cond, &mutex);    // c3
        int tmp = get();                         // c4
        Pthread_cond_signal(&cond);              // c5
        Pthread_mutex_unlock(&mutex);            // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);              // p1
        if (count == 1)                          // p2
            Pthread_cond_wait(&cond, &mutex);    // p3
        put(i);                                  // p4
        Pthread_cond_signal(&cond);              // p5
        Pthread_mutex_unlock(&mutex);            // p6
    }
}
```

P running

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep		Ready	p1	Running	0	
	Sleep		Ready	p2	Running	0	
	Sleep		Ready	p4	Running	1	Buffer now full

CV-based Producer-Consumer Implementation 1

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // c1
        if (count == 0)                       // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                      // c4
        Pthread_cond_signal(&cond);           // c5
        Pthread_mutex_unlock(&mutex);         // c6
        printf("%d\n", tmp);
    }
}
```

P running

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // p1
        if (count == 1)                       // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                               // p4
        Pthread_cond_signal(&cond);           // p5
        Pthread_mutex_unlock(&mutex);         // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep		Ready	p1	Running	0	
	Sleep		Ready	p2	Running	0	
	Sleep		Ready	p4	Running	1	Buffer now full
	Ready		Ready	p5	Running	1	T_{c1} awoken

CV-based Producer-Consumer Implementation 1

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);          // c1
        if (count == 0)                      // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                     // c4
        Pthread_cond_signal(&cond);          // c5
        Pthread_mutex_unlock(&mutex);        // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);          // p1
        if (count == 1)                      // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                              // p4
        Pthread_cond_signal(&cond);          // p5
        Pthread_mutex_unlock(&mutex);        // p6
    }
}
```

P running

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep		Ready	p1	Running	0	
	Sleep		Ready	p2	Running	0	
	Sleep		Ready	p4	Running	1	Buffer now full
	Ready		Ready	p5	Running	1	T_{c1} awoken
	Ready		Ready	p6	Running	1	
	Ready		Ready	p1	Running	1	
	Ready		Ready	p2	Running	1	

CV-based Producer-Consumer Implementation 1

P running

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);               // c1
        if (count == 0)                            // c2
            Pthread_cond_wait(&cond, &mutex);     // c3
        int tmp = get();                           // c4
        Pthread_cond_signal(&cond);               // c5
        Pthread_mutex_unlock(&mutex);             // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);               // p1
        if (count == 1)                            // p2
            Pthread_cond_wait(&cond, &mutex);     // p3
        put(i);                                    // p4
        Pthread_cond_signal(&cond);               // p5
        Pthread_mutex_unlock(&mutex);             // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep		Ready	p1	Running	0	
	Sleep		Ready	p2	Running	0	
	Sleep		Ready	p4	Running	1	Buffer now full
	Ready		Ready	p5	Running	1	T_{c1} awoken
	Ready		Ready	p6	Running	1	
	Ready		Ready	p1	Running	1	
	Ready		Ready	p2	Running	1	

CV-based Producer-Consumer Implementation 1

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // c1
        if (count == 0)                       // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                      // c4
        Pthread_cond_signal(&cond);           // c5
        Pthread_mutex_unlock(&mutex);         // c6
        printf("%d\n", tmp);
    }
}
```

C1 runnable

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // p1
        if (count == 1)                       // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                               // p4
        Pthread_cond_signal(&cond);           // p5
        Pthread_mutex_unlock(&mutex);         // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep		Ready	p1	Running	0	
	Sleep		Ready	p2	Running	0	
	Sleep		Ready	p4	Running	1	Buffer now full
	Ready		Ready	p5	Running	1	T_{c1} awoken
	Ready		Ready	p6	Running	1	
	Ready		Ready	p1	Running	1	
	Ready		Ready	p2	Running	1	
	Ready		Ready	p3	Sleep	1	Buffer full; sleep

CV-based Producer-Consumer Implementation 1

C2 running

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // c1
        if (count == 0)                       // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                      // c4
        Pthread_cond_signal(&cond);           // c5
        Pthread_mutex_unlock(&mutex);         // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // p1
        if (count == 1)                       // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                               // p4
        Pthread_cond_signal(&cond);           // p5
        Pthread_mutex_unlock(&mutex);         // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep		Ready	p1	Running	0	
	Sleep		Ready	p2	Running	0	
	Sleep		Ready	p4	Running	1	Buffer now full
	Ready		Ready	p5	Running	1	T_{c1} awoken
	Ready		Ready	p6	Running	1	
	Ready		Ready	p1	Running	1	
	Ready		Ready	p2	Running	1	
	Ready		Ready	p3	Sleep	1	Buffer full; sleep
	Ready	c1	Running		Sleep	1	T_{c2} sneaks in ...

CV-based Producer-Consumer Implementation 1

C2 running

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);              // c1
        if (count == 0)                          // c2
            Pthread_cond_wait(&cond, &mutex);    // c3
        int tmp = get();                         // c4
        Pthread_cond_signal(&cond);              // c5
        Pthread_mutex_unlock(&mutex);            // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);              // p1
        if (count == 1)                          // p2
            Pthread_cond_wait(&cond, &mutex);    // p3
        put(i);                                  // p4
        Pthread_cond_signal(&cond);              // p5
        Pthread_mutex_unlock(&mutex);            // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep		Ready	p1	Running	0	
	Sleep		Ready	p2	Running	0	
	Sleep		Ready	p4	Running	1	Buffer now full
	Ready		Ready	p5	Running	1	T_{c1} awoken
	Ready		Ready	p6	Running	1	
	Ready		Ready	p1	Running	1	
	Ready		Ready	p2	Running	1	
	Ready		Ready	p3	Sleep	1	Buffer full; sleep
	Ready	c1	Running		Sleep	1	T_{c2} sneaks in ...
	Ready	c2	Running		Sleep	1	
	Ready	c4	Running		Sleep	0	... and grabs data

CV-based Producer-Consumer Implementation 1

C2 running

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // c1
        if (count == 0)                        // c2
            Pthread_cond_wait(&cond, &mutex);  // c3
        int tmp = get();                       // c4
        Pthread_cond_signal(&cond);            // c5
        Pthread_mutex_unlock(&mutex);          // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // p1
        if (count == 1)                        // p2
            Pthread_cond_wait(&cond, &mutex);  // p3
        put(i);                                // p4
        Pthread_cond_signal(&cond);            // p5
        Pthread_mutex_unlock(&mutex);          // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep		Ready	p1	Running	0	
	Sleep		Ready	p2	Running	0	
	Sleep		Ready	p4	Running	1	Buffer now full
	Ready		Ready	p5	Running	1	T_{c1} awoken
	Ready		Ready	p6	Running	1	
	Ready		Ready	p1	Running	1	
	Ready		Ready	p2	Running	1	
	Ready		Ready	p3	Sleep	1	Buffer full; sleep
	Ready	c1	Running		Sleep	1	T_{c2} sneaks in ...
	Ready	c2	Running		Sleep	1	
	Ready	c4	Running		Sleep	0	... and grabs data
	Ready	c5	Running		Ready	0	T_p awoken

CV-based Producer-Consumer Implementation 1

C2 running

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // c1
        if (count == 0)                       // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                      // c4
        Pthread_cond_signal(&cond);           // c5
        Pthread_mutex_unlock(&mutex);         // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // p1
        if (count == 1)                       // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                               // p4
        Pthread_cond_signal(&cond);           // p5
        Pthread_mutex_unlock(&mutex);         // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep		Ready	p1	Running	0	
	Sleep		Ready	p2	Running	0	
	Sleep		Ready	p4	Running	1	Buffer now full
	Ready		Ready	p5	Running	1	T_{c1} awoken
	Ready		Ready	p6	Running	1	
	Ready		Ready	p1	Running	1	
	Ready		Ready	p2	Running	1	
	Ready		Ready	p3	Sleep	1	Buffer full; sleep
	Ready	c1	Running		Sleep	1	T_{c2} sneaks in ...
	Ready	c2	Running		Sleep	1	
	Ready	c4	Running		Sleep	0	... and grabs data
	Ready	c5	Running		Ready	0	T_p awoken
	Ready	c6	Running		Ready	0	

CV-based Producer-Consumer Implementation 1

C1 running

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // c1
        if (count == 0)                       // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                      // c4
        Pthread_cond_signal(&cond);           // c5
        Pthread_mutex_unlock(&mutex);         // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // p1
        if (count == 1)                       // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                               // p4
        Pthread_cond_signal(&cond);           // p5
        Pthread_mutex_unlock(&mutex);         // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep		Ready	p1	Running	0	
	Sleep		Ready	p2	Running	0	
	Sleep		Ready	p4	Running	1	Buffer now full
	Ready		Ready	p5	Running	1	T_{c1} awoken
	Ready		Ready	p6	Running	1	
	Ready		Ready	p1	Running	1	
	Ready		Ready	p2	Running	1	
	Ready		Ready	p3	Sleep	1	Buffer full; sleep
	Ready	c1	Running		Sleep	1	T_{c2} sneaks in ...
	Ready	c2	Running		Sleep	1	
	Ready	c4	Running		Sleep	0	... and grabs data
	Ready	c5	Running		Ready	0	T_p awoken
	Ready	c6	Running		Ready	0	
c4	Running		Ready		Ready	0	Oh oh! No data

CV-based Producer-Consumer Implementation 2

Single CV and while

```
cond_t  cond;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);             // p1
        while (count == 1)                      // p2
            Pthread_cond_wait(&cond, &mutex);   // p3
        put(i);                                 // p4
        Pthread_cond_signal(&cond);             // p5
        Pthread_mutex_unlock(&mutex);           // p6
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);             // c1
        while (count == 0)                      // c2
            Pthread_cond_wait(&cond, &mutex);   // c3
        int tmp = get();                        // c4
        Pthread_cond_signal(&cond);             // c5
        Pthread_mutex_unlock(&mutex);           // c6
        printf("%d\n", tmp);
    }
}
```

CV-based Producer-Consumer Implementation 2

```
cond_t  cond;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);               // p1
        while (count == 1)                        // p2
            Pthread_cond_wait(&cond, &mutex);     // p3
        put(i);                                   // p4
        Pthread_cond_signal(&cond);               // p5
        Pthread_mutex_unlock(&mutex);             // p6
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);               // c1
        while (count == 0)                        // c2
            Pthread_cond_wait(&cond, &mutex);     // c3
        int tmp = get();                          // c4
        Pthread_cond_signal(&cond);               // c5
        Pthread_mutex_unlock(&mutex);             // c6
        printf("%d\n", tmp);
    }
}
```

Single CV and while

What's the problem of this approach?

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // c1
        while (count == 0)                    // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                      // c4
        Pthread_cond_signal(&cond);           // c5
        Pthread_mutex_unlock(&mutex);         // c6
        printf("%d\n", tmp);
    }
}
```

C1 running

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // p1
        while (count == 1)                    // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                               // p4
        Pthread_cond_signal(&cond);           // p5
        Pthread_mutex_unlock(&mutex);         // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);              // c1
        while (count == 0)                       // c2
            Pthread_cond_wait(&cond, &mutex);    // c3
        int tmp = get();                         // c4
        Pthread_cond_signal(&cond);              // c5
        Pthread_mutex_unlock(&mutex);            // c6
        printf("%d\n", tmp);
    }
}
```

C2 running

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);              // p1
        while (count == 1)                       // p2
            Pthread_cond_wait(&cond, &mutex);    // p3
        put(i);                                  // p4
        Pthread_cond_signal(&cond);              // p5
        Pthread_mutex_unlock(&mutex);            // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep	c1	Running		Ready	0	
	Sleep	c2	Running		Ready	0	
	Sleep	c3	Sleep		Ready	0	Nothing to get

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // c1
        while (count == 0)                    // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                      // c4
        Pthread_cond_signal(&cond);           // c5
        Pthread_mutex_unlock(&mutex);         // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // p1
        while (count == 1)                    // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                               // p4
        Pthread_cond_signal(&cond);           // p5
        Pthread_mutex_unlock(&mutex);         // p6
    }
}
```

P running

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep	c1	Running		Ready	0	
	Sleep	c2	Running		Ready	0	
	Sleep	c3	Sleep		Ready	0	Nothing to get
	Sleep		Sleep	p1	Running	0	
	Sleep		Sleep	p2	Running	0	
	Sleep		Sleep	p4	Running	1	Buffer now full

```c
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // c1
        while (count == 0)                    // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                      // c4
        Pthread_cond_signal(&cond);           // c5
        Pthread_mutex_unlock(&mutex);         // c6
        printf("%d\n", tmp);
    }
}
```

```c
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // p1
        while (count == 1)                    // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                               // p4
        Pthread_cond_signal(&cond);           // p5
        Pthread_mutex_unlock(&mutex);         // p6
    }
}
```

P running

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep	c1	Running		Ready	0	
	Sleep	c2	Running		Ready	0	
	Sleep	c3	Sleep		Ready	0	Nothing to get
	Sleep		Sleep	p1	Running	0	
	Sleep		Sleep	p2	Running	0	
	Sleep		Sleep	p4	Running	1	Buffer now full
	Ready		Sleep	p5	Running	1	T_{c1} awoken

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // c1
        while (count == 0)                     // c2
            Pthread_cond_wait(&cond, &mutex);  // c3
        int tmp = get();                       // c4
        Pthread_cond_signal(&cond);            // c5
        Pthread_mutex_unlock(&mutex);          // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // p1
        while (count == 1)                     // p2
            Pthread_cond_wait(&cond, &mutex);  // p3
        put(i);                                // p4
        Pthread_cond_signal(&cond);            // p5
        Pthread_mutex_unlock(&mutex);          // p6
    }
}
```

P sleeping

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep	c1	Running		Ready	0	
	Sleep	c2	Running		Ready	0	
	Sleep	c3	Sleep		Ready	0	Nothing to get
	Sleep		Sleep	p1	Running	0	
	Sleep		Sleep	p2	Running	0	
	Sleep		Sleep	p4	Running	1	Buffer now full
	Ready		Sleep	p5	Running	1	T_{c1} awoken
	Ready		Sleep	p6	Running	1	
	Ready		Sleep	p1	Running	1	
	Ready		Sleep	p2	Running	1	
	Ready		Sleep	p3	Sleep	1	Must sleep (full)

C1 running

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // c1
        while (count == 0)                     // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                       // c4
        Pthread_cond_signal(&cond);            // c5
        Pthread_mutex_unlock(&mutex);          // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // p1
        while (count == 1)                     // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                                // p4
        Pthread_cond_signal(&cond);            // p5
        Pthread_mutex_unlock(&mutex);          // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep	c1	Running		Ready	0	
	Sleep	c2	Running		Ready	0	
	Sleep	c3	Sleep		Ready	0	Nothing to get
	Sleep		Sleep	p1	Running	0	
	Sleep		Sleep	p2	Running	0	
	Sleep		Sleep	p4	Running	1	Buffer now full
	Ready		Sleep	p5	Running	1	T_{c1} awoken
	Ready		Sleep	p6	Running	1	
	Ready		Sleep	p1	Running	1	
	Ready		Sleep	p2	Running	1	
	Ready		Sleep	p3	Sleep	1	Must sleep (full)
c2	Running		Sleep		Sleep	1	Recheck condition

C1 running

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // c1
        while (count == 0)                    // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                      // c4
        Pthread_cond_signal(&cond);           // c5
        Pthread_mutex_unlock(&mutex);         // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // p1
        while (count == 1)                    // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                               // p4
        Pthread_cond_signal(&cond);           // p5
        Pthread_mutex_unlock(&mutex);         // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep	c1	Running		Ready	0	
	Sleep	c2	Running		Ready	0	
	Sleep	c3	Sleep		Ready	0	Nothing to get
	Sleep		Sleep	p1	Running	0	
	Sleep		Sleep	p2	Running	0	
	Sleep		Sleep	p4	Running	1	Buffer now full
	Ready		Sleep	p5	Running	1	T_{c1} awoken
	Ready		Sleep	p6	Running	1	
	Ready		Sleep	p1	Running	1	
	Ready		Sleep	p2	Running	1	
	Ready		Sleep	p3	Sleep	1	Must sleep (full)
c2	Running		Sleep		Sleep	1	Recheck condition
c4	Running		Sleep		Sleep	0	T_{c1} grabs data

C1 running

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // c1
        while (count == 0)                    // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                      // c4
        Pthread_cond_signal(&cond);           // c5
        Pthread_mutex_unlock(&mutex);         // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // p1
        while (count == 1)                    // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                               // p4
        Pthread_cond_signal(&cond);           // p5
        Pthread_mutex_unlock(&mutex);         // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep	c1	Running		Ready	0	
	Sleep	c2	Running		Ready	0	
	Sleep	c3	Sleep		Ready	0	Nothing to get
	Sleep		Sleep	p1	Running	0	
	Sleep		Sleep	p2	Running	0	
	Sleep		Sleep	p4	Running	1	Buffer now full
	Ready		Sleep	p5	Running	1	T_{c1} awoken
	Ready		Sleep	p6	Running	1	
	Ready		Sleep	p1	Running	1	
	Ready		Sleep	p2	Running	1	
	Ready		Sleep	p3	Sleep	1	Must sleep (full)
c2	Running		Sleep		Sleep	1	Recheck condition
c4	Running		Sleep		Sleep	0	T_{c1} grabs data
c5	Running		Ready		Sleep	0	Oops! Woke T_{c2}

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);              // c1
        while (count == 0)                       // c2
            Pthread_cond_wait(&cond, &mutex);    // c3
        int tmp = get();                         // c4
        Pthread_cond_signal(&cond);              // c5
        Pthread_mutex_unlock(&mutex);            // c6
        printf("%d\n", tmp);
    }
}
```

C1 sleeping

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);              // p1
        while (count == 1)                       // p2
            Pthread_cond_wait(&cond, &mutex);    // p3
        put(i);                                  // p4
        Pthread_cond_signal(&cond);              // p5
        Pthread_mutex_unlock(&mutex);            // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep	c1	Running		Ready	0	
	Sleep	c2	Running		Ready	0	
	Sleep	c3	Sleep		Ready	0	Nothing to get
	Sleep		Sleep	p1	Running	0	
	Sleep		Sleep	p2	Running	0	
	Sleep		Sleep	p4	Running	1	Buffer now full
	Ready		Sleep	p5	Running	1	T_{c1} awoken
	Ready		Sleep	p6	Running	1	
	Ready		Sleep	p1	Running	1	
	Ready		Sleep	p2	Running	1	
	Ready		Sleep	p3	Sleep	1	Must sleep (full)
c2	Running		Sleep		Sleep	1	Recheck condition
c4	Running		Sleep		Sleep	0	T_{c1} grabs data
c5	Running		Ready		Sleep	0	Oops! Woke T_{c2}
c6	Running		Ready		Sleep	0	
c1	Running		Ready		Sleep	0	
c2	Running		Ready		Sleep	0	
c3	Sleep		Ready		Sleep	0	Nothing to get

C2 running

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // c1
        while (count == 0)                    // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                      // c4
        Pthread_cond_signal(&cond);           // c5
        Pthread_mutex_unlock(&mutex);         // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // p1
        while (count == 1)                    // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                               // p4
        Pthread_cond_signal(&cond);           // p5
        Pthread_mutex_unlock(&mutex);         // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep	c1	Running		Ready	0	
	Sleep	c2	Running		Ready	0	
	Sleep	c3	Sleep		Ready	0	Nothing to get
	Sleep		Sleep	p1	Running	0	
	Sleep		Sleep	p2	Running	0	
	Sleep		Sleep	p4	Running	1	Buffer now full
	Ready		Sleep	p5	Running	1	T_{c1} awoken
	Ready		Sleep	p6	Running	1	
	Ready		Sleep	p1	Running	1	
	Ready		Sleep	p2	Running	1	
	Ready		Sleep	p3	Sleep	1	Must sleep (full)
c2	Running		Sleep		Sleep	1	Recheck condition
c4	Running		Sleep		Sleep	0	T_{c1} grabs data
c5	Running		Ready		Sleep	0	Oops! Woke T_{c2}
c6	Running		Ready		Sleep	0	
c1	Running		Ready		Sleep	0	
c2	Running		Ready		Sleep	0	
c3	Sleep		Ready		Sleep	0	Nothing to get
	Sleep	c2	Running		Sleep	0	
	Sleep	c3	Sleep		Sleep	0	Everyone asleep...

C2 sleeping

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // c1
        while (count == 0)                    // c2
            Pthread_cond_wait(&cond, &mutex); // c3
        int tmp = get();                      // c4
        Pthread_cond_signal(&cond);           // c5
        Pthread_mutex_unlock(&mutex);         // c6
        printf("%d\n", tmp);
    }
}
```

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);           // p1
        while (count == 1)                    // p2
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);                               // p4
        Pthread_cond_signal(&cond);           // p5
        Pthread_mutex_unlock(&mutex);         // p6
    }
}
```

T_{c1}	State	T_{c2}	State	T_p	State	**Count**	*Comment*
c1	Running		Ready		Ready	0	
c2	Running		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep	c1	Running		Ready	0	
	Sleep	c2	Running		Ready	0	
	Sleep	c3	Sleep		Ready	0	Nothing to get
	Sleep		Sleep	p1	Running	0	
	Sleep		Sleep	p2	Running	0	
	Sleep		Sleep	p4	Running	1	Buffer now full
	Ready		Sleep	p5	Running	1	T_{c1} awoken
	Ready		Sleep	p6	Running	1	
	Ready		Sleep	p1	Running	1	
	Ready		Sleep	p2	Running	1	
	Ready		Sleep	p3	Sleep	1	Must sleep (full)
c2	Running		Sleep		Sleep	1	Recheck condition
c4	Running		Sleep		Sleep	0	T_{c1} grabs data
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c6	Running		Ready		Sleep	0	
c1	Running		Ready		Sleep	0	
c2	Running		Ready		Sleep	0	
c3	Sleep		Ready		Sleep	0	Nothing to get
	Sleep	c2	Running		Sleep	0	
	Sleep	c3	Sleep		Sleep	0	Everyone asleep...

CV-based Producer-Consumer Implementation 3

Two CVs and while

```
cond_t empty, fill;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);
        while (count == 1)
            Pthread_cond_wait(&empty, &mutex);
        put(i);
        Pthread_cond_signal(&fill);
        Pthread_mutex_unlock(&mutex);
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);
        while (count == 0)
            Pthread_cond_wait(&fill, &mutex);
        int tmp = get();
        Pthread_cond_signal(&empty);
        Pthread_mutex_unlock(&mutex);
        printf("%d\n", tmp);
    }
}
```

CV-based Producer-Consumer Implementation 3

```
cond_t empty, fill;
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void *producer(void *arg) {
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        put(i);
        Pthread_cond_signal(&fill);
        Pthread_mutex_unlock(&mutex);
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);
        while (count == 0)
            Pthread_cond_wait(&fill, &mutex);
        int tmp = get();
        Pthread_cond_signal(&empty);
        Pthread_mutex_unlock(&mutex);
        printf("%d\n", tmp);
    }
}
```

Two CVs and while

Using **two CVs** to distinguish two types of threads; in order to properly signal which thread should wake up

- Producer waits on **empty**
- Consumer waits on **fill**

Readers-Writers Problem

Readers-Writers Problem

- A data object (e.g. a file) is to be shared among several concurrent processes/threads
- A writer process/thread must have exclusive access to the data object
- Multiple reader processes/threads may access the shared data simultaneously without a problem

Reader-Writer Lock (sem-based)

```
typedef struct _rwlock_t {
  sem_t lock;      // binary semaphore (basic lock)
  sem_t writelock; // used to allow ONE writer or MANY readers
  int   readers;   // count of readers reading in critical section
} rwlock_t;

void rwlock_init(rwlock_t *rw) {
  rw->readers = 0;
  sem_init(&rw->lock, 0, 1);
  sem_init(&rw->writelock, 0, 1);
}

void rwlock_acquire_readlock(rwlock_t *rw) {
  sem_wait(&rw->lock);
  rw->readers++;
  if (rw->readers == 1)
    sem_wait(&rw->writelock); // first reader acquires writelock
  sem_post(&rw->lock);
}

void rwlock_release_readlock(rwlock_t *rw) {
  sem_wait(&rw->lock);
  rw->readers--;
  if (rw->readers == 0)
    sem_post(&rw->writelock); // last reader releases writelock
  sem_post(&rw->lock);
}

void rwlock_acquire_writelock(rwlock_t *rw) {
  sem_wait(&rw->writelock);
}

void rwlock_release_writelock(rwlock_t *rw) {
  sem_post(&rw->writelock);
}
```

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Initially, # readers is 0
binary `sem lock` set to 1
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}

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  sem_wait(&rw->writelock);
}

void rwlock_release_writelock(rwlock_t *rw) {
  sem_post(&rw->writelock);
}
```

Initially, # readers is 0
binary `sem` `lock` set to 1
`writelock` set to 1

Writer **cannot** be in CS when readers are!

Readers-Writers Problem: Writer Thread

```
rwlock_acquire_writelock(rw);
…
write is performed
…
rwlock_release_writelock(rw);
```

Readers-Writers Problem: Reader Thread

```
rwlock_acquire_readlock(rw);
              …
      read is performed
              …
rwlock_release_readlock(rw);
```

Well, is this solution Okay?

Readers-Writers Problem: Reader Thread

```
rwlock_acquire_readlock(rw);
            …
      read is performed
            …
rwlock_release_readlock(rw);
```

Well, is this solution Okay?

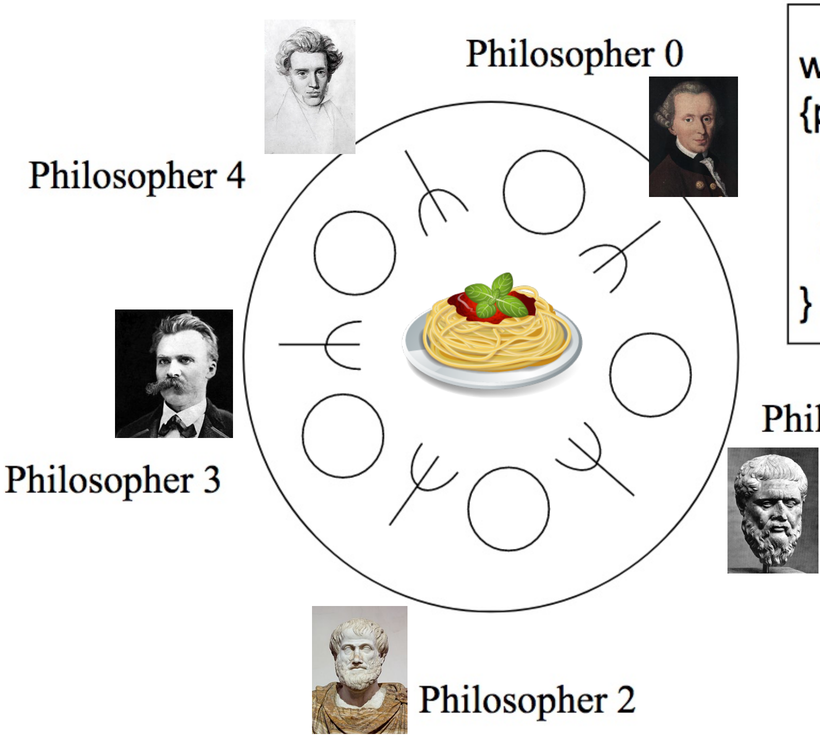
A: Technically it works. But **starvation** may happen

Starvation

- A process/thread that is forced to wait indefinitely in a synchronization program is said to be subject to starvation
  - In some execution scenarios, that process does not make any progress
  - Deadlocks imply starvation, but the reverse is not true

Dining-Philosophers Problem

Dining-Philosophers Problem




```
while(food available)
{pick up 2 adj. forks;
  eat;
  put down forks;
  think awhile;
}
```

- 5 philosophers share a common circular table. There are 5 forks (or chopsticks) and food (in the middle). When a philosopher gets hungry, he tries to pick up the closest forks

- A philosopher may pick up only one fork at a time, and cannot pick up a fork already in use. When done, he puts down both of his forks, one after the other

Shared data

```
sem_t forks[5];
```

Initially all semaphore values are 1

Dining-Philosophers Problem

- The basic loop of a philosopher

```
while (1) {
   think();
   getforks();
   eat();
   putforks();
}
```

??

Critical section

??

The Helper Functions

```
int left(int p)  { return p; }
int right(int p) { return (p + 1) % 5; }
```

`sem_t forks[5]`

- Each fork initialized to 1

```
void getforks() {
  sem_wait(forks[left(p)]);
  sem_wait(forks[right(p)]);
}

void putforks() {
  sem_post(forks[left(p)]);
  sem_post(forks[right(p)]);
}
```

Is this solution correct?

Simplest Example of A Deadlock

W/ only two philosophers and two forks

Thread 0	Interleaving	Thread 1

`sem_wait(fork[0])`
`sem_wait(fork[1])`
`sem_signal(fork[0])`
`sem_signal(fork[1])`
		`sem_wait(fork[1])`
		`sem_wait(fork[0])`
		`sem_signal(fork[1])`
		`sem_signal(fork[0])`

Simplest Example of A Deadlock

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`sem_signal(fork[0])`		`sem_signal(fork[1])`
`sem_signal(fork[1])`		`sem_signal(fork[0])`

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`sem_wait(fork[0])`		`sem_wait(fork[1])`
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`sem_signal(fork[0])`		`sem_signal(fork[1])`
`sem_signal(fork[1])`		`sem_signal(fork[0])`
	`sem_wait(fork[1])`	

Simplest Example of A Deadlock

W/ only two philosophers and two forks

Thread 0	Interleaving	Thread 1
`sem_wait(fork[0])`		`sem_wait(fork[1])`
`sem_wait(fork[1])`	`sem_wait(fork[0])`	`sem_wait(fork[0])`
`sem_signal(fork[0])`		`sem_signal(fork[1])`
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`sem_wait(fork[0])`
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`sem_signal(fork[1])`
	`sem_wait(fork[0])`
	
	`sem_wait(fork[1])`
	
	`sem_wait(fork[0])`
	wait...
	
	`sem_wait(fork[1])`
		`sem_wait(fork[1])`
		`sem_wait(fork[0])`
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Simplest Example of A Deadlock

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`sem_signal(fork[1])`
	`sem_wait(fork[0])`
	`sem_wait(fork[1])`
	`sem_wait(fork[0])`
	wait…
	`sem_wait(fork[1])`
	wait…
		`sem_wait(fork[1])`
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		`sem_signal(fork[1])`
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Review: Conditions for Deadlocks

- Mutually exclusive access of shared resources
  - Binary semaphore `fork[0]` and `fork[1]`

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  - Thread 0 waits for Thread 1 to signal(`fork[1]`) and
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Review: Conditions for Deadlocks

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  - Thread 0 waits for Thread 1 to signal(`fork[1]`) and
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- Hold and wait
  - Holding either `fork[0]` or `fork[1]` while waiting on the other

Review: Conditions for Deadlocks

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  - Thread 1 waits for Thread 0 to signal(`fork[0]`)
- Hold and wait
  - Holding either `fork[0]` or `fork[1]` while waiting on the other
- No preemption
  - Neither `fork[0]` and `fork[1]` can be removed from their respective holding threads

Why 5DP is Interesting?

- How to eat with your fellows without causing deadlocks
  - Circular arguments (the circular wait condition)
  - Not giving up on firmly held things (no preemption)
  - Infinite patience with half-baked schemes (hold some & wait for more)

Why 5DP is Interesting?

- ~~How to eat with your fellows without causing deadlocks~~ **How to mess with your fellows!**
  - Circular arguments (the circular wait condition)
  - Not giving up on firmly held things (no preemption)
  - Infinite patience with half-baked schemes (hold some & wait for more)

Dijkstra's Solution:
Break the Circular Wait Condition

- Change how forks are acquired by at least one of the philosophers
- Assume P0 – P4, 4 is the highest number

```
void getforks() {
  if (p == 4) {
    sem_wait(forks[right(p)]);
    sem_wait(forks[left(p)]);
  } else {
    sem_wait(forks[left(p)]);
    sem_wait(forks[right(p)]);
  }
}
```

Again, Starvation

- Subtle difference between deadlock and starvation
  - Once a set of processes are in a deadlock, there is no future execution sequence that can get them out of it!
  - In starvation, there does exist hope – some execution order may be favorable to the starving process although no guarantee it would ever occur

  - Rollback and retry are prone to starvation
  - Continuous arrival of higher priority process is another common starvation situation

Project 3 is out