

Concurrency: Condition Variables, PCP, 5DP

CS 571: *Operating Systems* (Spring 2021)

Lecture 8

Yue Cheng

Some material taken/derived from:

- Wisconsin CS-537 materials created by Remzi Arpacı-Dusseau.

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Condition Variables

Condition Variables

A parent waiting for its child

```
1 void *child(void *arg) {
2     printf("child\n");
3     // XXX how to indicate we are done?
4     return NULL;
5 }
6
7 int main(int argc, char *argv[]) {
8     printf("parent: begin\n");
9     pthread_t c;
10    Pthread_create(&c, NULL, child, NULL); // create child
11    // XXX how to wait for child?
12    printf("parent: end\n");
13    return 0;
14 }
```

Spin-based Approach

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

```
1  volatile int done = 0;
2
3  void *child(void *arg) {
4      printf("child\n");
5      done = 1;
6      return NULL;
7  }
8
9  int main(int argc, char *argv[]) {
10     printf("parent: begin\n");
11     pthread_t c;
12     Pthread_create(&c, NULL, child, NULL); // create child
13     while (done == 0)
14         ; // spin
15     printf("parent: end\n");
16     return 0;
17 }
```

Spin-based Approach

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

```
1  volatile int done = 0;
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3  void *child(void *arg) {
4      printf("child\n");
5      done = 1;
6      return NULL;
7  }
8
9  int main(int argc, char *argv[]) {
10     printf("parent: begin\n");
11     pthread_t c;
12     Pthread_create(&c, NULL, child, NULL); // create child
13     while (done == 0)
14         ; // spin
15     printf("parent: end\n");
16     return 0;
17 }
```

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

```
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;  
}  
  
1 → void thr_exit() {  
2     Pthread_mutex_lock(&m);  
3     Pthread_cond_signal(&c);  
4     Pthread_mutex_unlock(&m);  
5 }  
6  
7 void thr_join() {  
8     Pthread_mutex_lock(&m);  
9     Pthread_cond_wait(&c, &m);  
10    Pthread_mutex_unlock(&m);  
11 }
```

Broken Implementation 1

```
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;  
}  
  
1 → void thr_exit() {  
2     Pthread_mutex_lock(&m);  
3     Pthread_cond_signal(&c);  
4     Pthread_mutex_unlock(&m);  
5 }  
6  
7 void thr_join() {  
8     Pthread_mutex_lock(&m);  
9     Pthread_cond_wait(&c, &m);  
10    Pthread_mutex_unlock(&m);  
11 }
```

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

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 ... *sleeeeeeeeep forever ...*

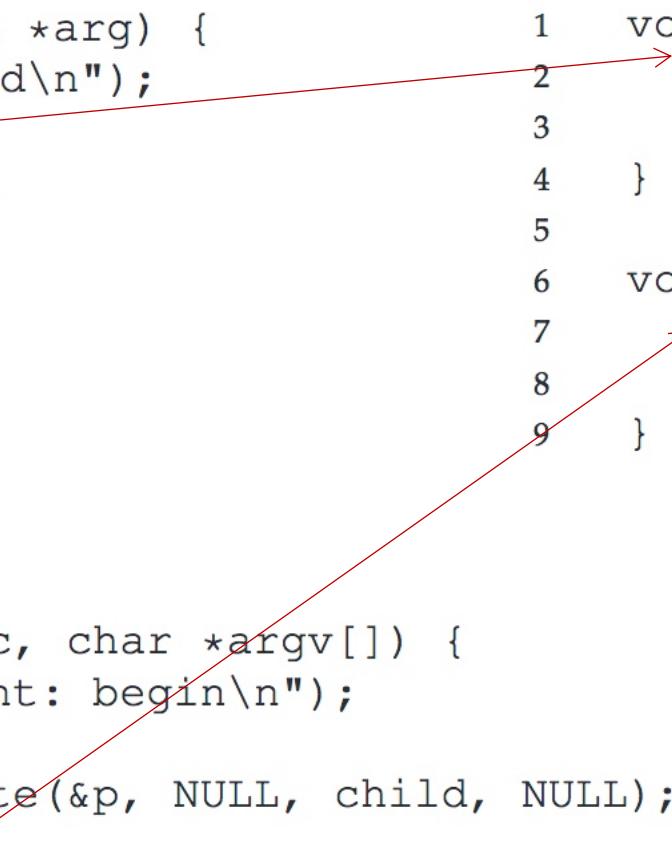
Child: a b c

```
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;  
}  
  
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;  
}  
  
1 void thr_exit() {  
2     done = 1;  
3     Pthread_cond_signal(&c);  
4 }  
5  
6 void thr_join() {  
7     if (done == 0)  
8         Pthread_cond_wait(&c);  
9 }
```



Broken Implementation 2

```
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;  
}
```

```
1 void thr_exit() {  
2     done = 1;  
3     Pthread_cond_signal(&c);  
4 }  
5  
6 void thr_join() {  
7     if (done == 0)  
8         Pthread_cond_wait(&c);  
9 }
```

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

```
void thread_exit() {  
    done = 1; // a  
    Cond_signal(&c); // b  
}  
  
void thread_join() {  
    Mutex_lock(&m); // w  
    while if(done == 0) // x  
        Cond_wait(&c, &m); // y  
    Mutex_unlock(&m); // z  
}
```

Annotations:

- A red arrow points from the `Cond_signal(&c);` line to the `done = 1;` line.
- A red arrow points from the `Cond_signal(&c);` line to the `Mutex_unlock(&m);` line.
- A red arrow points from the `if(done == 0)` line to the `done = 1;` line.

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

```
1 int done = 0;
2 pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
3 pthread_cond_t c = PTHREAD_COND_INITIALIZER;
4
5 void thr_exit() {
6     Pthread_mutex_lock(&m);
7     done = 1;
8     Pthread_cond_signal(&c);
9     Pthread_mutex_unlock(&m);
10 }
11
12 void *child(void *arg) {
13     printf("child\n");
14     thr_exit();
15     return NULL;
16 }
17
18 void thr_join() {
19     Pthread_mutex_lock(&m);
20     while (done == 0)
21         Pthread_cond_wait(&c, &m);
22     Pthread_mutex_unlock(&m);
23 }
24
25 int main(int argc, char *argv[]) {
26     printf("parent: begin\n");
27     pthread_t p;
28     Pthread_create(&p, NULL, child, NULL);
29     thr_join();
30     printf("parent: end\n");
31     return 0;
32 }
```

```
1 int done = 0;
2 pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
3 pthread_cond_t c = PTHREAD_COND_INITIALIZER;
4
5 void thr_exit() {
6     Pthread_mutex_lock(&m);
7     done = 1;
8     Pthread_cond_signal(&c);
9     Pthread_mutex_unlock(&m);
10 }
```

```
12 void *child(void *arg) {
13     printf("child\n");
14     thr_exit();
15     return NULL;
16 }
```

```
18 void thr_join() {
19     Pthread_mutex_lock(&m);
20     while (done == 0)
21         Pthread_cond_wait(&c, &m);
22     Pthread_mutex_unlock(&m);
23 }
```

```
25 int main(int argc, char *argv[]) {
26     printf("parent: begin\n");
27     pthread_t p;
28     Pthread_create(&p, NULL, child, NULL);
29     thr_join();
30     printf("parent: end\n");
31     return 0;
32 }
```

CV-based Parent-wait-for-child Approach

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);
    }
}
```

```
1  int buffer;
2  int count = 0; // initially, empty
3
4  void put(int value) {
5      assert(count == 0);
6      count = 1;
7      buffer = value;
8  }
9
10 int get() {
11     assert(count == 1);
12     count = 0;
13     return buffer;
14 }
```

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);
    }
}
```

```
1  int buffer;
2  int count = 0; // initially, empty
3
4  void put(int value) {
5      assert(count == 0);
6      count = 1;
7      buffer = value;
8  }
9
10 int get() {
11     assert(count == 1);
12     count = 0;
13     return buffer;
14 }
```

Put and Get routines
Single buffer

What's the problem of this approach?

CV-based Producer-Consumer Implementation 1

```
void *consumer(void *arg) { ← C1 running
    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) { ← P running
    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);
        Pthread_cond_signal(&cond); // p4
        Pthread_mutex_unlock(&mutex); // p5
    }
}

```

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);
    }
}

```

← 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

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

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

```

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	
	Ready		Ready	p5	Running	1	
	Ready		Ready	p6	Running	1	
	Ready		Ready	p1	Running	1	Buffer now full T_{c1} awoken
	Ready		Ready	p2	Running	1	

CV-based Producer-Consumer Implementation 1

```

void *consumer(void *arg) { ← C1 runnable
    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

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);
    }
}

```

C2 running

```

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

```

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

```

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)
            Pthread_cond_wait(&cond, &mutex); // p2
        put(i); // p3
        Pthread_cond_signal(&cond); // p4
        Pthread_mutex_unlock(&mutex); // p5
    }
}

```

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

```

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)
            Pthread_cond_wait(&cond, &mutex); // p2
        put(i); // p3
        Pthread_cond_signal(&cond); // p4
        Pthread_mutex_unlock(&mutex); // p5
    }
}

```

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

```

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)
            Pthread_cond_wait(&cond, &mutex); // p2
        put(i); // p3
        Pthread_cond_signal(&cond); // p4
        Pthread_mutex_unlock(&mutex); // p5
    }
}

```

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

```

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 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);
        Pthread_cond_signal(&cond); // p4
        Pthread_mutex_unlock(&mutex); // p5
    }
}

```

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

```
1  cond_t  cond;
2  mutex_t mutex;
3
4  void *producer(void *arg) {
5      int i;
6      for (i = 0; i < loops; i++) {
7          Pthread_mutex_lock(&mutex);           // p1
8          while (count == 1)                  // p2
9              Pthread_cond_wait(&cond, &mutex); // p3
10         put(i);                         // p4
11         Pthread_cond_signal(&cond);       // p5
12         Pthread_mutex_unlock(&mutex);     // p6
13     }
14 }
15
16 void *consumer(void *arg) {
17     int i;
18     for (i = 0; i < loops; i++) {
19         Pthread_mutex_lock(&mutex);           // c1
20         while (count == 0)                  // c2
21             Pthread_cond_wait(&cond, &mutex); // c3
22         int tmp = get();                  // c4
23         Pthread_cond_signal(&cond);       // c5
24         Pthread_mutex_unlock(&mutex);     // c6
25         printf("%d\n", tmp);
26     }
27 }
```

Single CV and while

CV-based Producer-Consumer Implementation 2

```
1  cond_t  cond;
2  mutex_t mutex;
3
4  void *producer(void *arg) {
5      int i;
6      for (i = 0; i < loops; i++) {
7          Pthread_mutex_lock(&mutex);           // p1
8          while (count == 1)                  // p2
9              Pthread_cond_wait(&cond, &mutex); // p3
10         put(i);                         // p4
11         Pthread_cond_signal(&cond);       // p5
12         Pthread_mutex_unlock(&mutex);     // p6
13     }
14 }
15
16 void *consumer(void *arg) {
17     int i;
18     for (i = 0; i < loops; i++) {
19         Pthread_mutex_lock(&mutex);           // c1
20         while (count == 0)                  // c2
21             Pthread_cond_wait(&cond, &mutex); // c3
22         int tmp = get();                  // c4
23         Pthread_cond_signal(&cond);       // c5
24         Pthread_mutex_unlock(&mutex);     // c6
25         printf("%d\n", tmp);
26     }
27 }
```

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)
            Pthread_cond_wait(&cond, &mutex); // p3
        put(i);
        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);
    }
}

```

P 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
	Sleep		Sleep	p1	Running	0	
	Sleep		Sleep	p2	Running	0	
	Sleep		Sleep	p4	Running	1	Buffer now full

```

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);
    }
}

```

P 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
	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);
    }
}

```

P sleeping ← P 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)

```

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
	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

```

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);
        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

```

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	
	Sleep	c1	Running		Ready	0	
	Sleep	c2	Running		Ready	0	
	Sleep	c3	Sleep		Ready	0	
	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	
	Sleep	c1	Running		Ready	0	
	Sleep	c2	Running		Ready	0	
	Sleep	c3	Sleep		Ready	0	
	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	

```

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	
	Sleep	c1	Running		Ready	0	
	Sleep	c2	Running		Ready	0	
	Sleep	c3	Sleep		Ready	0	
	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	
	Sleep	c2	Running		Sleep	0	
	Sleep	c3	Sleep		Sleep	0	Everyone asleep...

```

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 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	
	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	
	Ready		Sleep	p5	Running	1	Buffer now full
	Ready		Sleep	p6	Running	1	T_{c1} awoken
	Ready		Sleep	p1	Running	1	
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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

```
1 cond_t empty, fill;
2 mutex_t mutex;
3
4 void *producer(void *arg) {
5     int i;
6     for (i = 0; i < loops; i++) {
7         Pthread_mutex_lock(&mutex);
8         while (count == 1)
9             Pthread_cond_wait(&empty, &mutex);
10        put(i);
11        Pthread_cond_signal(&fill);
12        Pthread_mutex_unlock(&mutex);
13    }
14 }
15
16 void *consumer(void *arg) {
17     int i;
18     for (i = 0; i < loops; i++) {
19         Pthread_mutex_lock(&mutex);
20         while (count == 0)
21             Pthread_cond_wait(&fill, &mutex);
22         int tmp = get();
23         Pthread_cond_signal(&empty);
24         Pthread_mutex_unlock(&mutex);
25         printf("%d\n", tmp);
26     }
27 }
```

Two CVs and while

CV-based Producer-Consumer Implementation 3

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1 cond_t empty, fill;
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4 void *producer(void *arg) {
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16 void *consumer(void *arg) {
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21             Pthread_cond_wait(&fill, &mutex);
22         int tmp = get();
23         Pthread_cond_signal(&empty);
24         Pthread_mutex_unlock(&mutex);
25         printf("%d\n", tmp);
26     }
27 }
```

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

```
1  typedef struct _rwlock_t {
2      sem_t lock;          // binary semaphore (basic lock)
3      sem_t writelock;    // used to allow ONE writer or MANY readers
4      int   readers;      // count of readers reading in critical section
5  } rwlock_t;
6
7  void rwlock_init(rwlock_t *rw) {
8      rw->readers = 0;
9      sem_init(&rw->lock, 0, 1);
10     sem_init(&rw->writelock, 0, 1);
11 }
12
13 void rwlock_acquire_readlock(rwlock_t *rw) {
14     sem_wait(&rw->lock);
15     rw->readers++;
16     if (rw->readers == 1)
17         sem_wait(&rw->writelock); // first reader acquires writelock
18     sem_post(&rw->lock);
19 }
20
21 void rwlock_release_readlock(rwlock_t *rw) {
22     sem_wait(&rw->lock);
23     rw->readers--;
24     if (rw->readers == 0)
25         sem_post(&rw->writelock); // last reader releases writelock
26     sem_post(&rw->lock);
27 }
28
29 void rwlock_acquire_writelock(rwlock_t *rw) {
30     sem_wait(&rw->writelock);
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binary sem lock set to 1
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35 }
```

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: Writer Thread

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

Well, is this solution Okay?

Readers-Writers Problem: Writer Thread

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

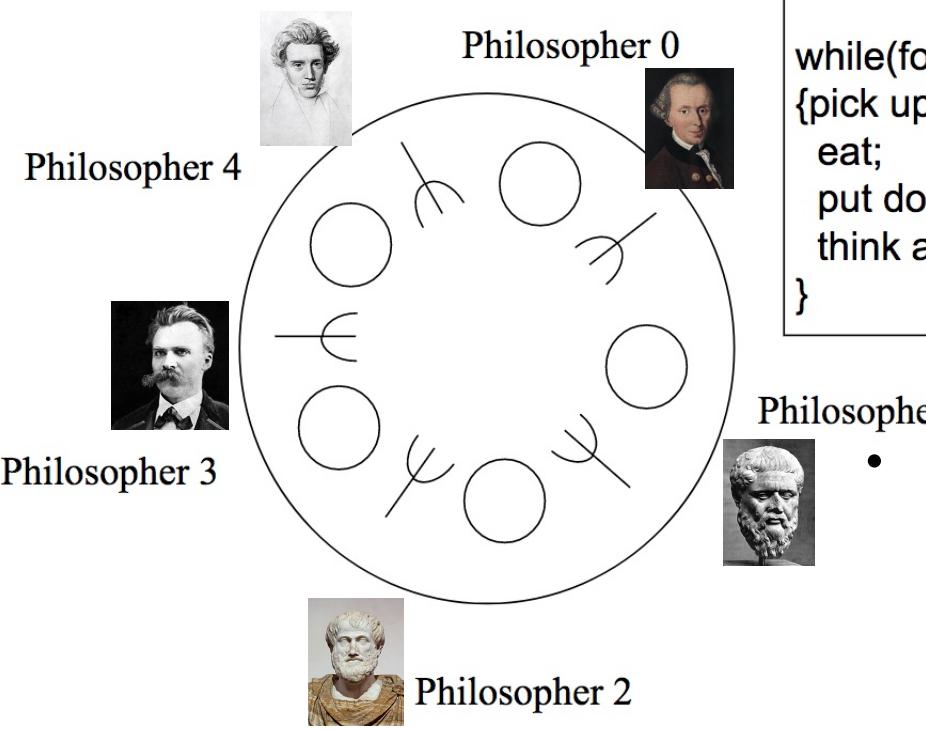
Well, is this solution Okay?
A: Technically it works. But
starvation may happen

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;
}
```

Philosopher 1

- 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(); → Critical section  
    putforks(); → ??  
}
```

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

```
1 void getforks() {
2     sem_wait(forks[left(p)]);
3     sem_wait(forks[right(p)]);
4 }
5
6 void putforks() {
7     sem_post(forks[left(p)]);
8     sem_post(forks[right(p)]);
9 }
```

Is this solution correct?

Simplest Example of A Deadlock

W/ only two philosophers and two forks

Thread 0

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

Interleaving

Thread 1

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

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W/ only two philosophers and two forks

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```
sem_wait(fork[0])
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Interleaving

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

```
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Interleaving

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

Thread 1

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

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W/ only two philosophers and two forks

Thread 0

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

Interleaving

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

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

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

wait...

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

Thread 1

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

Simplest Example of A Deadlock

W/ only two philosophers and two forks

Thread 0

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

Interleaving

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

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

```
sem_wait(fork[0])  
wait...
```

```
sem_wait(fork[1])  
wait...
```

Thread 1

```
sem_wait(fork[1])  
sem_wait(fork[0])  
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
 - Thread 1 waits for Thread 0 to signal(`fork[0]`)

Review: Conditions for Deadlocks

- Mutually exclusive access of shared resources
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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 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
- 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 starvation exists and what we can do about it?

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**)
- Why starvation exists and what we can do about it?

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

```
1 void getforks() {  
2     if (p == 4) {  
3         sem_wait(forks[right(p)]);  
4         sem_wait(forks[left(p)]);  
5     } else {  
6         sem_wait(forks[left(p)]);  
7         sem_wait(forks[right(p)]);  
8     }  
9 }
```

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