Operating Systems

Lecture 21: Condition Variables

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Concurrency Objectives

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- Mutual exclusion

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    - Join

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- Mutual exclusion
  - A & B don’t run at the same time
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  - A runs after B
  - Solved with?
    - Join
      - Implemented using condition variables

How to Join (run child before continuing parent)

```
void *child(void *arg) {
    printf("child\n");
    //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
    //how to wait for child?
    printf("parent: end\n");
    return 0;
}
```

How to Join: Spin based approach

```
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;
}
```

How to Join: Spin based approach

Initialising

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

Set done to 1 in child

How to Join: Spin based approach

```
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 wait for child to finish

How to Join: Spin based approach

```c
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
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How to Join: Spin based approach

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    Pthread_create(&c, NULL, child, NULL); // create child
    while (done == 0)
        ; // spin
    printf("parent: end\n");
    return 0;
}
```

Spin waiting is very costly!

Condition Variables

Condition Variables

- **Condition variable**

Condition Variables

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  - Queue of sleeping threads

Condition Variables

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  - Thread add themselves to queue with **wait**
  - Thread wake up threads on the queue with **signal**

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  - Puts caller to sleep + atomically releases lock
  - When awoken, reacquires lock before returning

Condition Variables

- **wait (cond_t *cv, mutex_t *lock)**
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  - Puts caller to sleep + atomically releases lock
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- **signal (cond_t *cv)**

Condition Variables

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- **signal (cond_t *cv)**
  - Wake a single waiting thread

Condition Variables

- **wait (cond_t *cv, mutex_t *lock)**
  - Assumes lock is held when wait() is called
  - Puts caller to sleep + atomically releases lock
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- **signal (cond_t *cv)**
  - Wake a single waiting thread
  - If there is no waiting thread, just return, do nothing

Exercise: order using condition variables Write thread_exit() an thread_join() using CVs

- **wait (cond_t *cv, mutex_t *lock)**
  - Assumes lock is held when wait() is called
  - Puts caller to sleep + atomically releases lock
  - When awoken, reacquires lock before returning
- **signal (cond_t *cv)**
  - Wake a single waiting thread
  - If there is no waiting thread, just return, do nothing

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


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

Exercise: order using condition variables Attempt #1

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

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
      Pthread_create(&c, NULL, child, NULL); // create child
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```

Exercise: order using condition variables
Attempt #1

```
void thread_exit {
     mutex_lock(&m)         //a
    cond_signal(&c)        //b
    mutex_unlock(&m) } //c
```

```
void *child(void *arg) {
    printf("child\n");
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int main(int argc, char *argv[]) {
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Exercise: order using condition variables Attempt #1

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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
    mutex_unlock(&m) }      //z
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```
void *child(void *arg) {
    printf("child\n");
    thread_exit()
    return NULL; }

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
     Pthread_create(&c, NULL, child, NULL); // create child
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void thread_exit {
    mutex_lock(&m)          //a
    cond_signal(&c)         //b
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void thread_join {
    mutex_lock(&m)          //x
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```
void *child(void *arg) {
    printf("child\n");
    thread_exit()
    return NULL; }

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // create child
    thread_join()
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void *child(void *arg) {
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int main(int argc, char *argv[]) {
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```
void thread_join {
    mutex_lock(&m)        //x
    cond_wait(&c, &m)     //y
    mutex_unlock(&m) }    //z
```

```
1   void *child(void *arg) {
2       printf("child\n");
3       thread_exit()
4       return NULL; }

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      thread_join()
12      printf("parent: end\n");
13      return 0; }
```

Order

Exercise: order using condition variables Attempt #1

```
void thread_exit {
    mutex_lock(&m)          //a
    cond_signal(&c)         //b
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```
void *child(void *arg) {
    printf("child\n");
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    return NULL; }

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

Order

Parent

Exercise: order using condition variables Attempt #1

```
void thread_exit {
    mutex_lock(&m)          //a
    cond_signal(&c)         //b
    mutex_unlock(&m) }      //c
```

```
void thread_join {
    mutex_lock(&m)          //x
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```
void *child(void *arg) {
    printf("child\n");
    thread_exit()
    return NULL; }


int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
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```

Order

Parent	Child

Exercise: order using condition variables Attempt #1

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void thread_exit {
    mutex_lock(&m)          //a
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int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // create child
    thread_join()
    printf("parent: end\n");
    return 0; }
```

Order

Parent	Child
x	

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Order

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x	
y	

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Order

Parent	Child
x	
y	
	a

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Order

Parent	Child
x	
y	
	a
	b

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Order

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y	
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Order

Parent	Child
	a

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Order

Parent	Child
	a
	b

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Order

Parent	Child
	a
	b
x	c

Exercise: order using condition variables Attempt #1

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void thread_exit {
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Parent	Child
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	b
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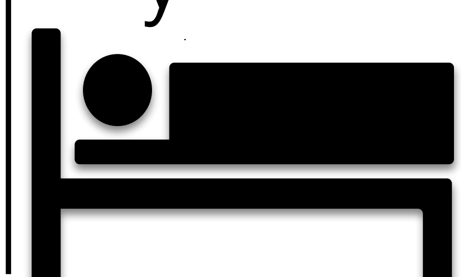
Order

Parent	Child
	a
	b
x	c
y	



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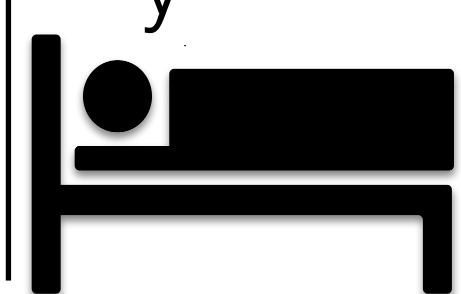
Order

Parent	Child
	a
	b
x	c
y	



Rule of Thumb #1

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- In addition to condition variables use another variable to capture state

Rule of Thumb #1

- In addition to condition variables use another variable to capture state
- CVs can be used to nudge threads when state changes

Exercise: order using condition variables Attempt #2

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

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

Exercise: order using condition variables Attempt #2

```
void thread_exit {
      Done  = 1                //a
   cond_signal(&c)        //b
```

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

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

Exercise: order using condition variables Attempt #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
```

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

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
     Pthread_create(&c, NULL, child, NULL); // create child
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```

Order

Exercise: order using condition variables Attempt #2

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      Done  = 1               //a
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```

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

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

Order

Parent

Exercise: order using condition variables Attempt #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
```

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

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

Order	
Parent	Child

Exercise: order using condition variables Attempt #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
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void *child(void *arg) {
    printf("child\n");
    thread_exit()
    return NULL; }

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

Order

Parent	Child
w	

Exercise: order using condition variables Attempt #2

```
void thread_exit {
    Done  = 1              //a
    cond_signal(&c)        //b
```

```
void thread_join {
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void *child(void *arg) {
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int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // create child
    thread_join()
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Order

Parent	Child
w	
x	

Exercise: order using condition variables Attempt #2

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void thread_exit {
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Order

Parent	Child
w	
x	
	a

Exercise: order using condition variables Attempt #2

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Order

Parent	Child
w	
x	
	a
	b

Exercise: order using condition variables Attempt #2

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void thread_exit {
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Order

Parent	Child
w	
x	
	a
	b
y	

Exercise: order using condition variables Attempt #2

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Order

Parent	Child
w	
x	
	a
	b
y	

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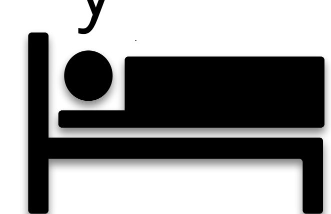
Order

Parent	Child
w	
x	
	a
	b
y	



Exercise: order using condition variables Correct Solution

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

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
     Pthread_create(&c, NULL, child, NULL); // create child
     thread_join()
     printf("parent: end\n");
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Exercise: order using condition variables Correct Solution

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void thread_exit {
    mutex_lock(&m)
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void *child(void *arg) {
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Exercise: order using condition variables Correct Solution

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void thread_exit {
    mutex_lock(&m)
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Rule of Thumb #2

Rule of Thumb #2

- Wait and signal while holding the lock

The Producer Consumer Problem

The Producer Consumer Problem

- Producers produce data and place it on a shared resource

The Producer Consumer Problem

- Producers produce data and place it on a shared resource
- Example:

The Producer Consumer Problem

- Producers produce data and place it on a shared resource
- Example:
  - Multi-threaded web server:

The Producer Consumer Problem

- Producers produce data and place it on a shared resource
- Example:
  - Multi-threaded web server:
    - Multiple request coming in concurrently - Producers

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- Example:
  - Multi-threaded web server:
    - Multiple request coming in concurrently - Producers
    - Multiple responses concurrently - Consumers

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- Producers produce data and place it on a shared resource
- Example:
  - Multi-threaded web server:
    - Multiple request coming in concurrently - Producers
    - Multiple responses concurrently - Consumers
  - Bounded buffer

The Producer Consumer Problem

- Producers produce data and place it on a shared resource
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  - Multi-threaded web server:
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  - Bounded buffer
    - grep foo file.txt | wc –l

The Producer Consumer Problem

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  - Multi-threaded web server:
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  - Bounded buffer
    - grep foo file.txt | wc –l
    - The grep process is the producer.

The Producer Consumer Problem

- Producers produce data and place it on a shared resource
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  - Multi-threaded web server:
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    - grep foo file.txt | wc –l
    - The grep process is the producer.
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The Producer Consumer Problem

- Producers produce data and place it on a shared resource
- Example:
  - Multi-threaded web server:
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    - Multiple responses concurrently - Consumers
  - Bounded buffer
    - grep foo file.txt | wc –l
    - The grep process is the producer.
    - The wc process is the consumer.
    - Between them is an in-kernel bounded buffer.

The Producer Consumer Problem

- Producers produce data and place it on a shared resource
- Example:
  - Multi-threaded web server:
    - Multiple request coming in concurrently - Producers
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  - Bounded buffer
    - grep foo file.txt | wc –l
    - The grep process is the producer.
    - The wc process is the consumer.
    - Between them is an in-kernel bounded buffer.
-

The Producer Consumer Problem

Bounded Buffer

The Producer Consumer Problem

Bounded Buffer

The Producer Consumer Problem

Producer adds to the buffer

Bounded Buffer

The Producer Consumer Problem

Producer adds to the buffer

Bounded Buffer

The Producer Consumer Problem

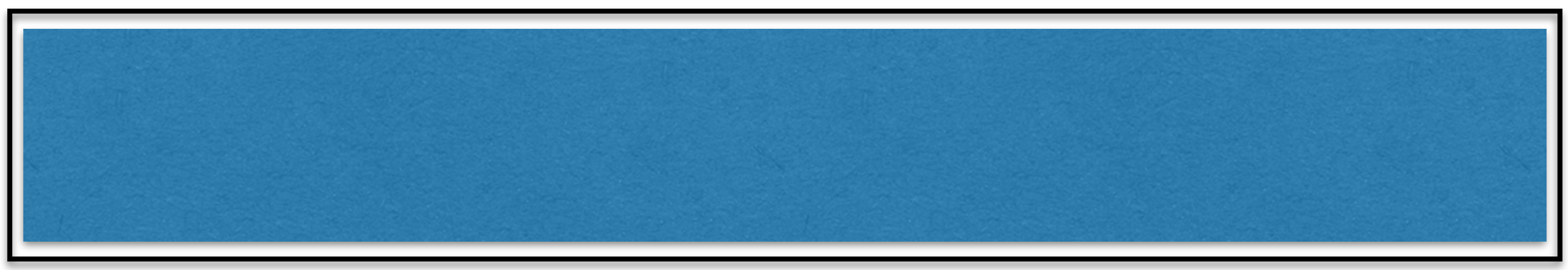
Producer adds to the buffer

Consumer removes from the buffer

Bounded Buffer

The Producer Consumer Problem

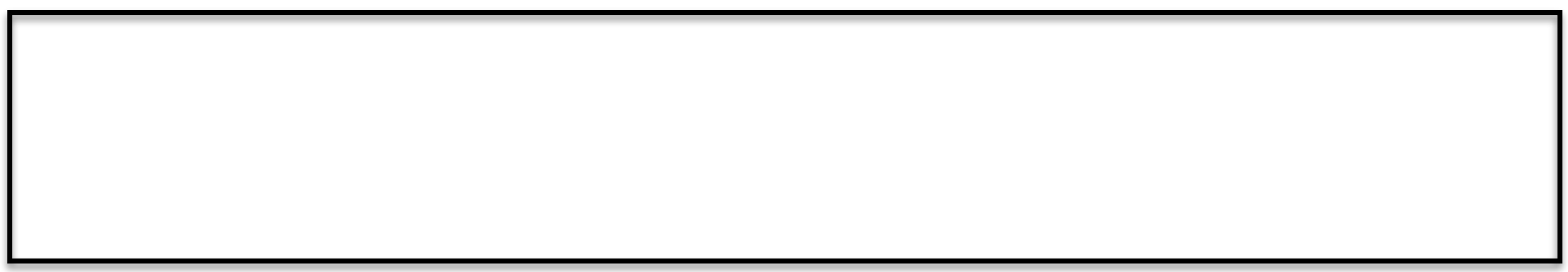
Buffer Full - Producer(s) have to wait



Bounded Buffer

The Producer Consumer Problem

Buffer Empty - Consumer(s) have to wait



Bounded Buffer

The Producer Consumer Problem (Buffer size =1)

```
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;
}
```

The Producer Consumer Problem (Buffer size =1)

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

void put(int value) {
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```

Insert into buffer (produce) only if buffer is empty

The Producer Consumer Problem (Buffer size =1)

```
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;
}
```

Delete from buffer (consume) only if buffer is full

The Producer Consumer Problem (Buffer size =1) [Attempt #1]

```
void *producer(void *arg) {
int i;
int loops = (int) arg;
for (i = 0; i < loops; i++) {
put(i);
}
}

void *consumer(void *arg) {
int i;
while (1) {
int tmp = get();
printf("%d\n", tmp);
}
}
```

The Producer Consumer Problem (Buffer size =1) [Attempt #1]

```
void *producer(void *arg) {
int i;
int loops = (int) arg;
for (i = 0; i < loops; i++) {
put(i);
}
}

void *consumer(void *arg) {
 int i;
 while (1) {
 int tmp = get();
 printf("%d\n", tmp);
 }
 }
```

Producer puts an integer into the shared buffer loops number of times.

The Producer Consumer Problem (Buffer size =1) [Attempt #1]

```c
void *producer(void *arg) {
int i;
int loops = (int) arg;
for (i = 0; i < loops; i++) {
put(i);
}
}

void *consumer(void *arg) {
int i;
while (1) {
int tmp = get();
printf("%d\n", tmp);
}
}
```

Consumer gets data out of the buffer.

The Producer Consumer Problem (Buffer size =1) [Attempt #1]

```
void *producer(void *arg) {
int i;
int loops = (int) arg;
for (i = 0; i < loops; i++) {
put(i);
}
}

void *consumer(void *arg) {
int i;
while (1) {
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printf("%d\n", tmp);
}
}
```

The Producer Consumer Problem (Buffer size =1) [Attempt #1]

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void *producer(void *arg) {
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```

What's the problem

The Producer Consumer Problem (Buffer size =1) [Attempt #1]

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int i;
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What’s the problem with this approach?

The Producer Consumer Problem (Buffer size =1) [Attempt #1]

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int i;
while (1) {
int tmp = get();
printf("%d\n", tmp);
}
}
```

What’s the problem with this approach?

Multiple threads accessing

The Producer Consumer Problem (Buffer size =1) [Attempt #1]

```
void *producer(void *arg) {
int i;
int loops = (int) arg;
for (i = 0; i < loops; i++) {
put(i);
}
}

void *consumer(void *arg) {
int i;
while (1) {
int tmp = get();
printf("%d\n", tmp);
}
}
```

What's the problem with this approach?

Multiple threads accessing shared resource without locking

The Producer Consumer Problem (Buffer size =1) [Attempt #2]

```
void *producer(void *arg) {
int i;
int loops = (int) arg;
for (i = 0; i < loops; i++) {
Pthread_mutex_lock(&mutex);
put(i);
Pthread_mutex_unlock(&mutex);}
}
  void *consumer(void *arg) {
int i;
while (1) { Pthread_mutex_lock(&mutex);
int tmp = get();
Pthread_mutex_unlock(&mutex);
printf("%d\n", tmp);
} }
```

The Producer Consumer Problem (Buffer size =1) [Attempt #2]

```
void *producer(void *arg) {
int i;
int loops = (int) arg;
for (i = 0; i < loops; i++) {
Pthread_mutex_lock(&mutex);
put(i);
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 while (1) { Pthread_mutex_lock(&mutex);
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 } }
```

What’s the problem

The Producer Consumer Problem (Buffer size =1) [Attempt #2]

```c
void *producer(void *arg) {
int i;
int loops = (int) arg;
for (i = 0; i < loops; i++) {
Pthread_mutex_lock(&mutex);
put(i);
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}
  void *consumer(void *arg) {
 int i;
 while (1) { Pthread_mutex_lock(&mutex);
 int tmp = get();
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```

What's the problem with this approach?

The Producer Consumer Problem (Buffer size =1) [Attempt #2]

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void *producer(void *arg) {
int i;
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printf("%d\n", tmp);
} }
```

What's the problem with this approach?

No explicit waiting

The Producer Consumer Problem (Buffer size =1) [Attempt #2]

```
void *producer(void *arg) {
int i;
int loops = (int) arg;
for (i = 0; i < loops; i++) {
Pthread_mutex_lock(&mutex);
put(i);
Pthread_mutex_unlock(&mutex);}
}
  void *consumer(void *arg) {
int i;
while (1) { Pthread_mutex_lock(&mutex);
int tmp = get();
Pthread_mutex_unlock(&mutex);
printf("%d\n", tmp);
} }
```

What's the problem with this approach?

No explicit waiting on empty and full buffer