Operating Systems and Concurrency

Lecture 11: Concurrency
COMP2007 (G52OSC)

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Goals

Today

- Parallel dining philosophers
- Readers/writers problem

The Dining Philosophers Problem

Solutions 2: Global Mutex/Semaphore

```
1  sem_t eating;
2
3  void * philosopher(void * id) {
4    int i = (int) id;
5    int left = (i + N - 1) % N;
6    int right = i % N;
7    while(1) {
8      printf("%d is thinking\n", i);
9      printf("%d is hungry\n", i);
10     sem_wait(&eating);       /**** semaphore ****/
11     sem_wait(&forks[left]);
12     sem_wait(&forks[right]);
13     printf("%d is eating\n", i);
14     sem_post(&forks[left]);
15     sem_post(&forks[right]);
16     sem_post(&eating);       /**** semaphore ****/
17   }
18 }
```

Question in a Previous Year:

"Can I initialise the value of the `eating` *semaphore to 2 to create maximum parallelism"*

- Would it deadlock?
- Do we get maximum parallelism?

The Dining Philosophers Problem

Solutions 2: Illustration

```
Philosopher 1
wait(&eating)
wait(&forks[0])
wait(&forks[1])
...
// eating
...
post(&forks[0])
post(&forks[1])
post(&eating)
```

```
Philosopher 2
wait(&eating)
wait(&forks[1])
wait(&forks[2])
...
// eating
...
post(&forks[1])
post(&forks[2])
post(&eating)
```

```
Philosopher 3
wait(&eating)
wait(&forks[2])
wait(&forks[3])
...
// eating
...
post(&forks[2])
post(&forks[3])
post(&eating)
```

```
Philosopher 4
wait(&eating)
wait(&forks[3])
wait(&forks[4])
...
// eating
...
post(&forks[3])
post(&forks[4])
post(&eating)
```

```
Philosopher 5
wait(&eating)
wait(&forks[4])
wait(&forks[0])
...
// eating
...
post(&forks[4])
post(&forks[0])
post(&eating)
```

The Dining Philosophers Problem

Solutions 2: Illustration

Philosopher 1	Philosopher 2	Philosopher 3	Philosopher 4	Philosopher 5
wait(&eating)	**wait(&eating)2=>1**	wait(&eating)	wait(&eating)	wait(&eating)
wait(&forks[0])	wait(&forks[1])	wait(&forks[2])	wait(&forks[3])	wait(&forks[4])
wait(&forks[1])	wait(&forks[2])	wait(&forks[3])	wait(&forks[4])	wait(&forks[0])
...	...	...	...	...
// eating	// eating	// eating	// eating	// eating
...	...	...	...	...
post(&forks[0])	post(&forks[1])	post(&forks[2])	post(&forks[3])	post(&forks[4])
post(&forks[1])	post(&forks[2])	post(&forks[3])	post(&forks[4])	post(&forks[0])
post(&eating)	post(&eating)	post(&eating)	post(&eating)	post(&eating)

The Dining Philosophers Problem

Solutions 2: Illustration

Philosopher 1	Philosopher 2	Philosopher 3	Philosopher 4	Philosopher 5
wait(&eating)	wait(&eating)	wait(&eating)	wait(&eating)	wait(&eating)
wait(&forks[0])	**wait(&forks[1])1=>0**	wait(&forks[2])	wait(&forks[3])	wait(&forks[4])
wait(&forks[1])	wait(&forks[2])	wait(&forks[3])	wait(&forks[4])	wait(&forks[0])
...	...	...	...	...
// eating	// eating	// eating	// eating	// eating
...	...	...	...	...
post(&forks[0])	post(&forks[1])	post(&forks[2])	post(&forks[3])	post(&forks[4])
post(&forks[1])	post(&forks[2])	post(&forks[3])	post(&forks[4])	post(&forks[0])
post(&eating)	post(&eating)	post(&eating)	post(&eating)	post(&eating)

The Dining Philosophers Problem

Solutions 2: Illustration

Philosopher 1	Philosopher 2	Philosopher 3	Philosopher 4	Philosopher 5
wait(&eating)	wait(&eating)	wait(&eating)	wait(&eating)	wait(&eating)
wait(&forks[0])	wait(&forks[1])	wait(&forks[2])	wait(&forks[3])	wait(&forks[4])
wait(&forks[1])	**wait(&forks[2])1=>0**	wait(&forks[3])	wait(&forks[4])	wait(&forks[0])
...	...	...	...	...
// eating	// eating	// eating	// eating	// eating
...	...	...	...	...
post(&forks[0])	post(&forks[1])	post(&forks[2])	post(&forks[3])	post(&forks[4])
post(&forks[1])	post(&forks[2])	post(&forks[3])	post(&forks[4])	post(&forks[0])
post(&eating)	post(&eating)	post(&eating)	post(&eating)	post(&eating)

The Dining Philosophers Problem

Solutions 2: Illustration

Philosopher 1	Philosopher 2	Philosopher 3	Philosopher 4	Philosopher 5
wait(&eating)	wait(&eating)	**wait(&eating)1=>0**	wait(&eating)	wait(&eating)
wait(&forks[0])	wait(&forks[1])	wait(&forks[2])	wait(&forks[3])	wait(&forks[4])
wait(&forks[1])	wait(&forks[2])	wait(&forks[3])	wait(&forks[4])	wait(&forks[0])
...	...	...	...	...
// eating	// eating	// eating	// eating	// eating
...	...	...	...	...
post(&forks[0])	post(&forks[1])	post(&forks[2])	post(&forks[3])	post(&forks[4])
post(&forks[1])	post(&forks[2])	post(&forks[3])	post(&forks[4])	post(&forks[0])
post(&eating)	post(&eating)	post(&eating)	post(&eating)	post(&eating)

The Dining Philosophers Problem

Solutions 2: Illustration

Philosopher 1	Philosopher 2	Philosopher 3	Philosopher 4	Philosopher 5
wait(&eating)	wait(&eating)	wait(&eating)	wait(&eating)	wait(&eating)
wait(&forks[0])	wait(&forks[1])	**wait(&forks[2])** 0=>-1	wait(&forks[3])	wait(&forks[4])
wait(&forks[1])	**wait(&forks[2])**	wait(&forks[3])	wait(&forks[4])	wait(&forks[0])
...	...	...	...	...
// eating	// eating	// eating	// eating	// eating
...	...	...	...	...
post(&forks[0])	post(&forks[1])	post(&forks[2])	post(&forks[3])	post(&forks[4])
post(&forks[1])	post(&forks[2])	post(&forks[3])	post(&forks[4])	post(&forks[0])
post(&eating)	post(&eating)	post(&eating)	post(&eating)	post(&eating)

The Dining Philosophers Problem

Solutions 2: Illustration

Philosopher 1	Philosopher 2	Philosopher 3	Philosopher 4	Philosopher 5
wait(&eating)	wait(&eating)	wait(&eating)	**wait(&eating)0=>-1**	wait(&eating)
wait(&forks[0])	wait(&forks[1])	wait(&forks[2])	wait(&forks[3])	wait(&forks[4])
wait(&forks[1])	wait(&forks[2])	wait(&forks[3])	wait(&forks[4])	wait(&forks[0])
...	...	...	...	...
// eating	// eating	// eating	// eating	// eating
...	...	...	...	...
post(&forks[0])	post(&forks[1])	post(&forks[2])	post(&forks[3])	post(&forks[4])
post(&forks[1])	post(&forks[2])	post(&forks[3])	post(&forks[4])	post(&forks[0])
post(&eating)	post(&eating)	post(&eating)	post(&eating)	post(&eating)

The Dining Philosophers Problem

Solutions 2: Illustration

```
Philosopher 1
wait(&eating)
wait(&forks[0])
wait(&forks[1])
...
// eating
...
post(&forks[0])
post(&forks[1])
post(&eating)
```

```
Philosopher 2
wait(&eating)
wait(&forks[1])
wait(&forks[2])
...
// eating
...
post(&forks[1])
post(&forks[2])
post(&eating)
```

```
Philosopher 3
wait(&eating)
wait(&forks[2])
wait(&forks[3])
...
// eating
...
post(&forks[2])
post(&forks[3])
post(&eating)
```

```
Philosopher 4
wait(&eating)
wait(&forks[3])
wait(&forks[4])
...
// eating
...
post(&forks[3])
post(&forks[4])
post(&eating)
```

```
Philosopher 5
wait(&eating)-1=>-2
wait(&forks[4])
wait(&forks[0])
...
// eating
...
post(&forks[4])
post(&forks[0])
post(&eating)
```

The Dining Philosophers Problem

Solutions 2: Illustration

Philosopher 1	Philosopher 2	Philosopher 3	Philosopher 4	Philosopher 5
wait(&eating)-2=>-3	wait(&eating)	wait(&eating)	wait(&eating)	wait(&eating)
wait(&forks[0])	wait(&forks[1])	wait(&forks[2])	wait(&forks[3])	wait(&forks[4])
wait(&forks[1])	wait(&forks[2])	wait(&forks[3])	wait(&forks[4])	wait(&forks[0])
...	...	...	...	...
// eating	// eating	// eating	// eating	// eating
...	...	...	...	...
post(&forks[0])	post(&forks[1])	post(&forks[2])	post(&forks[3])	post(&forks[4])
post(&forks[1])	post(&forks[2])	post(&forks[3])	post(&forks[4])	post(&forks[0])
post(&eating)	post(&eating)	post(&eating)	post(&eating)	post(&eating)

The Dining Philosophers Problem

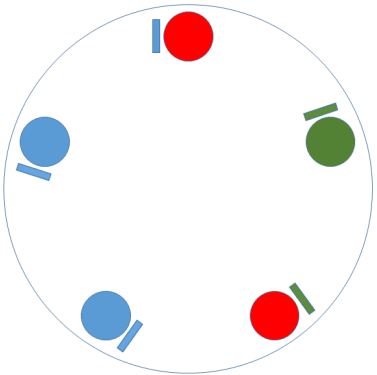
Solution 3: Maximum Parallelism

- A **more sophisticated solution** is necessary to allow **maximum parallelism**
- The solution uses:
  - `state[N]`: one **state variable** for every philosopher (`THINKING`, `HUNGRY`, `EATING`)
  - `phil[N]`: one **semaphore per *philosopher*** (i.e., **not forks**, **initialised to 0**)
    - The philosopher **goes to sleep** if one of his/her neighbours are eating
    - The **neighbours wake up the philosopher** if they have finished eating
  - `sync`: one **semaphore**/**mutex** to enforce **mutual exclusion** of the critical section (while updating the **states**)

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

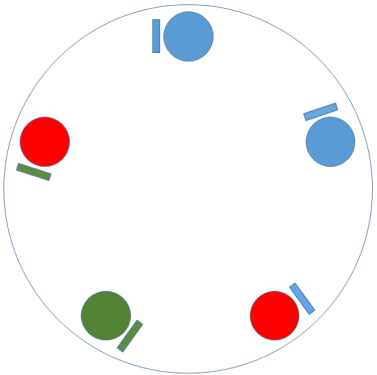
- A philosopher can only **start eating** if his/her **neighbours are not eating**



The Dining Philosophers Problem

Solution 3: Maximum Parallelism

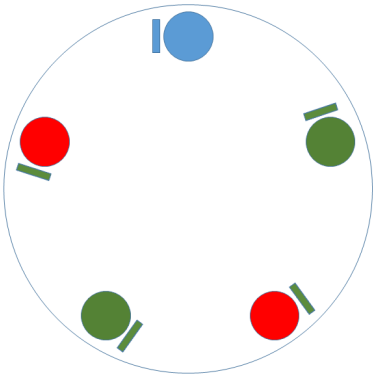
- A philosopher can only **start eating** if his/her **neighbours are not eating**



The Dining Philosophers Problem

Solution 3: Maximum Parallelism

- A philosopher can only **start eating** if his/her **neighbours are not eating**



The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
#define N 5
#define THINKING 1
#define HUNGRY 2
#define EATING 3

int state[N] = {THINKING, THINKING, THINKING, THINKING, THINKING};
sem_t phil[N];  // sends philosopher to sleep
sem_t sync;
```

```
void * philosopher(void * id) {
  int i = *((int *) id);
  while(1) {
    printf("%d is thinking\n", i);
    take_forks(i);
    printf("%d is eating\n", i);
    put_forks(i);
  }
}
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
1  void take_forks(int i) {
2    sem_wait(&sync);
3    state[i] = HUNGRY;
4    test(i);
5    sem_post(&sync);
6    sem_wait(&phil[i]);
7  }
```

```
1  void test(int i) {
2    int left = (i + N - 1) % N;
3    int right = (i + 1) % N;
4    if(state[i] == HUNGRY && state[left] != EATING && state[right] != EATING) {
5      state[i] = EATING;
6      sem_post(&phil[i]);
7    }
8  }
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
1  void put_forks(int i) {
2    int left = (i + N - 1) % N;
3    int right = (i + 1) % N;
4    sem_wait(&sync);
5    state[i] = THINKING;
6    test(left);
7    test(right);
8    sem_post(&sync);
9  }
```

```
1  void test(int i) {
2    int left = (i + N - 1) % N;
3    int right = (i + 1) % N;
4    if(state[i] == HUNGRY && state[left] != EATING && state[right] != EATING) {
5      state[i] = EATING;
6      sem_post(&phil[i]);
7    }
8  }
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)  // 1 => 0
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])  // 0 => 1
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)  // 0 => 1
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])  // 0 => 1
}
post(&sync)
wait(&phil[3])  // 1 => 0

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)  // 1 => 0
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])//assume == -1 (wakeup)

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])  // -1 => 0
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])  // -1 => 0
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4]) // assume -1 (wakeup)

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)  // 0 => 1
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)  // 1 => 0
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)  // 0 => 1
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])  // 0 => -1 (sleeping)

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)  // 1 => 0
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Dining Philosophers Problem

Solution 3: Maximum Parallelism

```
Philosopher 2
(left = 1, right = 3)

wait(&sync)
state[2]=HUNGRY
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
post(&sync)
wait(&phil[2])

// EAT EAT EAT EAT EAT

wait(&sync)
state[2] = THINK
// test neighbours
if(state[1]==HUNGRY
  && state[5]!=EAT
  && state[2]!=EAT){
  state[1]=EAT
  post(&phil[1])
}
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])  // -1 => 0
}
post(&sync)
```

```
Philosopher 3
(left = 2, right = 4)

wait(&sync)
state[3]=HUNGRY
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
post(&sync)
wait(&phil[3])  // wakeup

// EAT EAT EAT EAT EAT

wait(&sync)
state[3] = THINK
// test neighbours
if(state[2]==HUNGRY
  && state[1]!=EAT
  && state[3]!=EAT){
  state[2]=EAT
  post(&phil[2])
}
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
```

```
Philosopher 4
(left = 3, right = 5)

wait(&sync)
state[4]=HUNGRY
if(state[4]==HUNGRY
  && state[3]!=EAT
  && state[5]!=EAT){
  state[4]=EAT
  post(&phil[4])
}
post(&sync)
wait(&phil[4])

// EAT EAT EAT EAT EAT

wait(&sync)
state[4] = THINK
// test neighbours
if(state[3]==HUNGRY
  && state[2]!=EAT
  && state[4]!=EAT){
  state[3]=EAT
  post(&phil[3])
}
if(state[5]==HUNGRY
  && state[4]!=EAT
  && state[1]!=EAT){
  state[5]=EAT
  post(&phil[5])
}
post(&sync)
```

The Readers – Writers Problem

Description

- Concurrent database processes are readers and/or writers, files, I/O devices, etc.
- **Reading** a record (variable) can happen **in parallel** without problems, **writing needs synchronisation** (i.e. exclusive access)
- **Different solutions** exist to the readers/writers problem
  - Solution 1: naive implementation with **limited parallelism**
  - Solution 2: **readers** receive **priority**: **no reader is kept waiting** (unless a writer already has access, **writers may starve**)
  - Solution 3: **writing** is performed **as soon as possibly** (**readers may starve**)

The Readers – Writers Problem

Solution 1: No Parallelism

```
1  void * reader(void * arg) {
2    while(1) {
3      pthread_mutex_lock(&sync);
4      printf("reading record\n");
5      pthread_mutex_unlock(&sync);
6    }
7  }
```

```
1  void * writer(void * writer) {
2    while(1) {
3      pthread_mutex_lock(&sync);
4      printf("writing\n");
5      pthread_mutex_unlock(&sync);
6    }
7  }
```

The Readers – Writers Problem

Solution 2: Readers First

- Solution 1: prevents **parallel reading**
- Solution 2: **allows parallel reading**
- A correct implementation of solution 2 requires:
  - `iReadCount`: an integer tracking the number of readers
    - If `iReadCount > 0`: writers are blocked (`sem_wait(rwSync)`)
    - If `iReadCount == 0`: writers are released (`sem_post(rwSync)`)
    - If already writing, readers must wait
  - `sync`: a mutex for mutual exclusion of `iReadCount`
  - `rwSync`: a semaphore that **synchronises the readers and writers**, set by the **first/last reader**

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync); // 1=>0
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;  // 0=>1
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);  // 1=>0
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync); // 0=>1

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);  // 0=>-1
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);  // 1=>0
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;  // 1=>0
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);  // -1=>0
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync); // wakeup
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);  // 0=>1
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
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{
  while(1)
  {
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    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
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    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);  // 0=>1
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync); // 1=>0
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync); // 1=>0
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++; // 0=>1
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync); // 0=>-1 (sleep)
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);   (wakeup)
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);  // -1=>0
  }
}
```

The Readers – Writers Problem

Solution 2: Readers First

```
void * reader(void * arg)
{
  while(1)
  {
    sem_wait(&sync);
    iReadCount++;
    if(iReadCount == 1)
      sem_wait(&rwSync);
    sem_post(&sync);

    printf("reading record\n");

    sem_wait(&sync);
    iReadCount--;
    if(iReadCount == 0)
      sem_post(&rwSync);
    sem_post(&sync);
  }
}
```

```
void * writer(void * writer)
{
  while(1)
  {
    sem_wait(&rwSync);
    printf("writing\n");
    sem_post(&rwSync);
  }
}
```

Recap

Take-Home Message

- **Dining philosophers** with **improved parallelism** and **maximum parallelism**
- Readers/writers problem
  - Solution with **limited/no parallelism**
  - Solution with **priority for the readers**