6.033 Spring 2020

Lecture #4

- Bounded Buffers
- Concurrency
- Locks
operating systems enforce modularity on a single machine using virtualization in order to enforce modularity + build an effective operating system

1. programs shouldn’t be able to refer to (and corrupt) each others’ memory

2. programs should be able to communicate

3. programs should be able to share a CPU without one program halting the progress of the others
operating systems enforce modularity on a single machine using virtualization

in order to enforce modularity + build an effective operating system

1. programs shouldn’t be able to refer to (and corrupt) each others’ memory
   → virtual memory

2. programs should be able to communicate
   → bounded buffers (virtualize communication links)

3. programs should be able to share a CPU without one program halting the progress of the others
   → assume one program per CPU (for today)

**today’s goal**: implement bounded buffers so that programs can communicate
bounded buffer: a buffer that stores (up to) N messages
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bounded buffer API:

send(m)
m <- receive()
send(bb, message):
    while True:
        if bb.in - bb.out < N:
            bb.buf[bb.in mod N] <- message
            bb.in <- bb.in + 1
        return

receive(bb):
    while True:
        if bb.out < bb.in:
            message <- bb.buf[bb.out mod N]
            bb.out <- bb.out + 1
        return message
send(bb, message):
    while True:
        if bb.in - bb.out < N:
            bb.in <- bb.in + 1
            bb.buf[bb.in mod N] <- message
        return

receive(bb):
    while True:
        if bb.out < bb.in:
            message <- bb.buf[bb.out mod N]
            bb.out <- bb.out + 1
        return message
send(bb, message):
    while True:
        if bb.in - bb.out < N:
            bb.in <- bb.in + 1
            bb.buf[bb.in-1 mod N] <- message
        return

receive(bb):
    while True:
        if bb.out < bb.in:
            message <- bb.buf[bb.out mod N]
            bb.out <- bb.out + 1
        return message
send(bb, message):
    while True:
        if bb.in - bb.out < N:
            bb.buf[bb.in mod N] <- message
            bb.in <- bb.in + 1
        return

receive(bb):
    while True:
        if bb.out < bb.in:
            message <- bb.buf[bb.out mod N]
            bb.out <- bb.out + 1
        return message

incorrect if we swap these statements!
1: `send(bb, message):`
2: while True:
3:     if `bb.in - bb.out < N`:
4:         `bb.buf[bb.in mod N] <- message`
5:         `bb.in <- bb.in + 1`
6:     return
locks: allow only one CPU to be inside a piece of code at a time
**locks**: allow only one CPU to be inside a piece of code at a time

**lock API**:
- `acquire(l)`
- `release(l)`
int buf[6];
int in = 0;
struct lock lck;

send(int x)
{
    buf[in%6] = x;
    in = in + 1;
}

cpu_one()
{
    send(1);
    send(2);
    send(3);
}

cpu_two()
{
    send(101);
    send(102);
    send(103);
}
```c
int buf[6];
int in = 0;
struct lock lck;

send(int x)
{
    buf[in%6] = x;
    in = in + 1;
}

cpu_one()
{
    send(1);
    send(2);
    send(3);
}

cpu_two()
{
    send(101);
    send(102);
    send(103);
}

example output:

101 102 103 1 2 3
101 102 1 0 2 3
1 102 103 0 2 3
1 2 3
```
int buf[6];
int in = 0;
struct lock lck;

send(int x)
{
    buf[in%6] = x;
    in = in + 1;
}

cpu_one()
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    send(1);
    send(2);
    send(3);
}

cpu_two()
{
    send(101);
    send(102);
    send(103);
}

example output:
101 102 103 1 2 3
101 102 1 0 2 3
1 102 103 0 2 3
1 2 3
correct!
int buf[6];
int in = 0;
struct lock lck;

send(int x)
{
    buf[in%6] = x;
    in = in + 1;
}

cpu_one()
cpu_two()
{
    send(1);
    send(2);
    send(3);
}

    send(101);
    send(102);
    send(103);

101 102 103 1 2 3
101 102 1 0 2 3
1 102 103 0 2 3
1 2 3

correct!
empty spots in buffer
int buf[6];
int in = 0;
struct lock lck;

send(int x)
{
    buf[in%6] = x;
in = in + 1;
}

cpu_one()
{
    send(1);
    send(2);
    send(3);
}

cpu_two()
{
    send(101);
    send(102);
    send(103);
}

---

element output:

- Correct!
- Empty spots in buffer
- Too few elements in buffer
int buf[6];
int in = 0;
struct lock lck;

send(int x)
{
    acquire(&lck);
    buf[in] = x;
    release(&lck);
    acquire(&lck);
    in = in + 1;
    release(&lck);
}

cpu_one()
{
    send(1);
    send(2);
    send(3);
}

cpu_two()
{
    send(101);
    send(102);
    send(103);
}
int buf[6];
int in = 0;
struct lock lck;

send(int x)
{
    acquire(&lck);
    buf[in] = x;
    release(&lck);
    acquire(&lck);
    in = in + 1;
    release(&lck);
}

cpu_one()
{
    send(1);
    send(2);
    send(3);
}

cpu_two()
{
    send(101);
    send(102);
    send(103);
}

example output:

101 102 103 1 2 3
1 0 2 0 3 0
101 1 0 2 0 3
101 1 103 2 0 3
```c
int buf[6];
int in = 0;
struct lock lck;

send(int x)
{
    acquire(&lck);
    buf[in] = x;
    release(&lck);
    acquire(&lck);
    in = in + 1;
    release(&lck);
}

cpu_one()
{
    send(1);
    send(2);
    send(3);
}

cpu_two()
{
    send(101);
    send(102);
    send(103);
}

example output:
correct! 101 102 103 1 2 3
1 0 2 0 3 0
101 1 0 2 0 3
101 1 103 2 0 3
```
int buf[6];
int in = 0;
struct lock lck;

send(int x)
{
    acquire(&lck);
    buf[in] = x;
    release(&lck);
    acquire(&lck);
in = in + 1;
    release(&lck);
}

cpu_one()
{
    send(1);
    send(2);
    send(3);
}

cpu_two()
{
    send(101);
    send(102);
    send(103);
}

example output:
101 102 103 1 2 3
1 0 2 0 3 0
101 1 0 2 0 3
101 1 103 2 0 3

empty spots in buffer

correct!
int buf[6];
int in = 0;
struct lock lck;

send(int x)
{
    acquire(&lck);
    buf[in] = x;
    in = in + 1;
    release(&lck);
}

cpu_one()
{
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cpu_two()
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int buf[6];
int in = 0;
struct lock lck;

send(int x)
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    buf[in] = x;
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    release(&lck);
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cpu_one()
{
    send(1);
    send(2);
    send(3);
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cpu_two()
{
    send(101);
    send(102);
    send(103);
}

example output:
101 1 102 2 103 3
101 102 1 103 2 3
1 101 2 102 3 103
101 102 1 103 2 3
```
int buf[6];
int in = 0;
struct lock lck;

send(int x)
{
    acquire(&lck);
    buf[in] = x;
    in = in + 1;
    release(&lck);
}

cpu_one()
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    send(1);
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cpu_two()
{
    send(101);
    send(102);
    send(103);
}

example output:

101 1 102 2 103 3
101 102 1 103 2 3
1 101 2 102 3 103
101 102 1 103 2 3

correct!
send(bb, message):
    while True:
        if bb.in - bb.out < N:
            acquire(bb.lock)
            bb.buf[bb.in mod N] <- message
            bb.in <- bb.in + 1
            release(bb.lock)
    return
send(bb, message):
    while True:
        if bb.in - bb.out < N:
            acquire(bb.lock)
            bb.buf[bb.in mod N] <- message
            bb.in <- bb.in + 1
            release(bb.lock)
    return

problem: second sender could end up writing to full buffer
send(bb, message):
  acquire(bb.lock)
  while True:
    if bb.in - bb.out < N:
      bb.buf[bb.in mod N] <- message
      bb.in <- bb.in + 1
  release(bb.lock)
  return
send(bb, message):
    acquire(bb.lock)
    while True:
        if bb.in - bb.out < N:
            bb.buf[bb.in mod N] <- message
            bb.in <- bb.in + 1
        release(bb.lock)
    return

problem: deadlock if buffer is full
(receive needs to acquire bb.lock to make space in buffer)
**Problem:** deadlock if buffer is full

\[(\text{receive needs to acquire } \text{bb.lock} \text{ to make space in buffer})\]
Problem: deadlock if buffer is full
(receive needs to acquire bb.lock to make space in buffer)

send(bb, message):

acquire(bb.lock)

while True:
    if bb.in - bb.out < N:
        bb.buf[bb.in mod N] <- message
        bb.in <- bb.in + 1
    release(bb.lock)

return
send(bb, message):
    acquire(bb.lock)
    while bb.in - bb.out == N:
        release(bb.lock)
        acquire(bb.lock)
    bb.buf[bb.in mod N] <- message
    bb.in <- bb.in + 1
    release(bb.lock)
    return
Filesystem move

\[
\text{move}(\text{dir1}, \text{dir2}, \text{filename}): \\
\text{unlink}(\text{dir1}, \text{filename}) \\
\text{link}(\text{dir2}, \text{filename})
\]
move(dir1, dir2, filename):
    acquire(fs_lock)
    unlink(dir1, filename)
    link(dir2, filename)
    release(fs_lock)
move(\texttt{dir1, dir2, filename}): 
\hspace{1cm} \texttt{acquire(fs\_lock)} \\
\hspace{1cm} \texttt{unlink(\texttt{dir1, filename})} \\
\hspace{1cm} \texttt{link(\texttt{dir2, filename})} \\
\hspace{1cm} \texttt{release(fs\_lock)}

\textbf{problem:} poor performance
Filesystem move

```python
move(dir1, dir2, filename):
    acquire(dir1.lock)
    unlink(dir1, filename)
    release(dir1.lock)
    acquire(dir2.lock)
    link(dir2, filename)
    release(dir2.lock)
```
Filesystem move

move(dir1, dir2, filename):
    acquire(dir1.lock)
    unlink(dir1, filename)
    release(dir1.lock)
    acquire(dir2.lock)
    link(dir2, filename)
    release(dir2.lock)

problem: inconsistent state is exposed
Filesystem move

move(dir1, dir2, filename):
    acquire(dir1.lock)
    acquire(dir2.lock)
    unlink(dir1, filename)
    link(dir2, filename)
    release(dir1.lock)
    release(dir2.lock)
Move (dir1, dir2, filename):

acquire(dir1.lock)
acquire(dir2.lock)
unlink(dir1, filename)
link(dir2, filename)
release(dir1.lock)
release(dir2.lock)

Problem: deadlock
move(dir1, dir2, filename):
    if dir1.inum < dir2.inum:
        acquire(dir1.lock)
        acquire(dir2.lock)
    else:
        acquire(dir2.lock)
        acquire(dir1.lock)
    unlink(dir1, filename)
    link(dir2, filename)
    release(dir1.lock)
    release(dir2.lock)
move(dir1, dir2, filename):
    if dir1.inum < dir2.inum:
        acquire(dir1.lock)
        acquire(dir2.lock)
    else:
        acquire(dir2.lock)
        acquire(dir1.lock)
    unlink(dir1, filename)
    link(dir2, filename)
    release(dir1.lock)
    release(dir2.lock)

could release dir1’s lock here instead
Implementing Locks

acquire(lock):
    while lock != 0:
        do nothing
    lock = 1

release(lock):
    lock = 0
Implementing Locks

acquire(\textit{lock}): \\
\hspace{1em} \text{while } \textit{lock} \neq 0: \\
\hspace{2em} \textit{do nothing} \\
\hspace{1em} \textit{lock} = 1

release(\textit{lock}): \\
\hspace{1em} \textit{lock} = 0

\textbf{problem:} race condition \\
(need locks to implement locks!)
acquire:(lock):
    do:
        \texttt{r} <- 1
        \texttt{XCHG r, lock}
    while \texttt{r} == 1

release:(lock):
    \texttt{lock} = 0
• **Bounded buffers** allow programs to communicate, completing the second step of enforcing modularity on a single machine. They are tricky to implement due to **concurrency**.

• **Locks** allow us to implement **atomic actions**. Determining the correct locking discipline is tough thanks to race conditions, deadlock, and performance issues.