

CS162 Operating Systems and Systems Programming Lecture 8

Readers-Writers Language Support for Synchronization

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Review: Implementation of Locks by Disabling Interrupts

- Key idea: maintain a lock variable and impose mutual exclusion only during operations on that variable

```
int value = FREE; 
```

```
Acquire() {
    disable interrupts;
    if (value == BUSY) {
        put thread on wait queue;
        Go to sleep();
        // Enable interrupts?
    } else {
        value = BUSY;
    }
    enable interrupts;
}

Release() {
    disable interrupts;
    if (anyone on wait queue) {
        take thread off wait queue;
        Place on ready queue;
    } else {
        value = FREE;
    }
    enable interrupts;
}
```

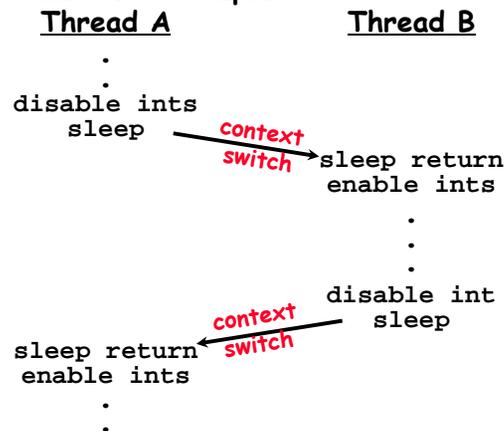
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Review: How to Re-enable After Sleep()? ---

- In Nachos, since ints are disabled when you call sleep:
 - Responsibility of the next thread to re-enable ints
 - When the sleeping thread wakes up, returns to acquire and re-enables interrupts



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Review: Locks using test&set ---

- Can we build test&set locks without busy-waiting?
 - Can't entirely, but can minimize!
 - Idea: only busy-wait to atomically check lock value

```
int guard = 0;
int value = FREE; 
```

```
Acquire() {
    // Short busy-wait time
    while (test&set(guard));
    if (value == BUSY) {
        put thread on wait queue;
        go to sleep() & guard = 0;
    } else {
        value = BUSY;
        guard = 0;
    }
}

Release() {
    // Short busy-wait time
    while (test&set(guard));
    if anyone on wait queue {
        take thread off wait queue;
        Place on ready queue;
    } else {
        value = FREE;
        guard = 0;
    }
}
```

- Note: sleep has to be sure to reset the guard variable
 - Why can't we do it just before or just after the sleep?

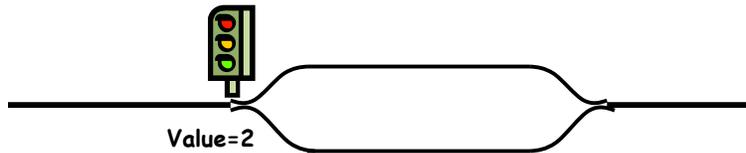
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Review: Semaphores

- **Definition:** a Semaphore has a non-negative integer value and supports the following two operations:
 - **P():** an atomic operation that waits for semaphore to become positive, then decrements it by 1
 - » Think of this as the wait() operation
 - **V():** an atomic operation that increments the semaphore by 1, waking up a waiting P, if any
 - » Think of this as the signal() operation
 - Only time can set integer directly is at initialization time
- Semaphore from railway analogy
 - Here is a semaphore initialized to 2 for resource control:



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Goals for Today

- Continue with Synchronization Abstractions
 - Monitors and condition variables
- Readers-Writers problem and solution
- Language Support for Synchronization

Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne. Many slides generated from my lecture notes by Kubiatowicz.

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Review: Full Solution to Bounded Buffer

```
Semaphore fullBuffer = 0; // Initially, no coke
Semaphore emptyBuffers = numBuffers;
// Initially, num empty slots
Semaphore mutex = 1; // No one using machine

Producer(item) {
    emptyBuffers.P(); // Wait until space
    mutex.P(); // Wait until buffer free
    Enqueue(item);
    mutex.V();
    fullBuffers.V(); // Tell consumers there is
                    // more coke
}

Consumer() {
    fullBuffers.P(); // Check if there's a coke
    mutex.P(); // Wait until machine free
    item = Dequeue();
    mutex.V();
    emptyBuffers.V(); // tell producer need more
    return item;
}
```

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Discussion about Solution

- Why asymmetry?
 - Producer does: emptyBuffer.P(), fullBuffer.V()
 - Consumer does: fullBuffer.P(), emptyBuffer.V()
 - Is order of P's important?
 - Yes! Can cause deadlock:
- ```
Producer(item) {
 mutex.P(); // Wait until buffer free
 emptyBuffers.P(); // Could wait forever!
 Enqueue(item);
 mutex.V();
 fullBuffers.V(); // Tell consumers more coke
}
```
- Is order of V's important?
    - No, except that it might affect scheduling efficiency
  - What if we have 2 producers or 2 consumers?
    - Do we need to change anything?

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## Motivation for Monitors and Condition Variables

- Semaphores are a huge step up, but:
  - They are confusing because they are dual purpose:
    - » Both mutual exclusion and scheduling constraints
    - » Example: the fact that flipping of P's in bounded buffer gives deadlock is not immediately obvious
  - Cleaner idea: Use **locks** for mutual exclusion and **condition variables** for scheduling constraints
- Definition: **Monitor**: a lock and zero or more condition variables for managing concurrent access to shared data
  - Use of Monitors is a programming paradigm
  - Some languages like Java provide monitors in the language
- The lock provides mutual exclusion to shared data:
  - Always acquire before accessing shared data structure
  - Always release after finishing with shared data
  - Lock initially free

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## Simple Monitor Example (version 1)

- Here is an (infinite) synchronized queue

```
Lock lock;
Queue queue;

AddToQueue(item) {
 lock.Acquire(); // Lock shared data
 queue.enqueue(item); // Add item
 lock.Release(); // Release Lock
}

RemoveFromQueue() {
 lock.Acquire(); // Lock shared data
 item = queue.dequeue(); // Get next item or null
 lock.Release(); // Release Lock
 return(item); // Might return null
}
```

- Not very interesting use of "Monitor"
  - It only uses a lock with no condition variables
  - Cannot put consumer to sleep if no work!

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## Condition Variables

- How do we change the RemoveFromQueue() routine to wait until something is on the queue?
  - Could do this by keeping a count of the number of things on the queue (with semaphores), but error prone
- **Condition Variable**: a queue of threads waiting for something *inside* a critical section
  - Key idea: allow sleeping inside critical section by atomically releasing lock at time we go to sleep
  - Contrast to semaphores: Can't wait inside critical section
- Operations:
  - **Wait(&lock)**: Atomically release lock and go to sleep. Re-acquire lock later, before returning.
  - **Signal()**: Wake up one waiter, if any
  - **Broadcast()**: Wake up all waiters
- Rule: Must hold lock when doing condition variable ops!
  - In Birrell paper, he says can perform signal() outside of lock - IGNORE HIM (this is only an optimization)

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## Complete Monitor Example (with condition variable)

- Here is an (infinite) synchronized queue

```
Lock lock;
Condition dataready;
Queue queue;

AddToQueue(item) {
 lock.Acquire(); // Get Lock
 queue.enqueue(item); // Add item
 dataready.signal(); // Signal any waiters
 lock.Release(); // Release Lock
}

RemoveFromQueue() {
 lock.Acquire(); // Get Lock
 while (queue.isEmpty()) {
 dataready.wait(&lock); // If nothing, sleep
 }
 item = queue.dequeue(); // Get next item
 lock.Release(); // Release Lock
 return(item);
}
```

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## Mesa vs. Hoare monitors

- Need to be careful about precise definition of signal and wait. Consider a piece of our dequeue code:

```
while (queue.isEmpty()) {
 dataready.wait(&lock); // If nothing, sleep
}
item = queue.dequeue(); // Get next item
```

- Why didn't we do this?

```
if (queue.isEmpty()) {
 dataready.wait(&lock); // If nothing, sleep
}
item = queue.dequeue(); // Get next item
```

- Answer: depends on the type of scheduling
  - Hoare-style (most textbooks):
    - » Signaler gives lock, CPU to waiter; waiter runs immediately
    - » Waiter gives up lock, processor back to signaler when it exits critical section or if it waits again
  - Mesa-style (Nachos, most real operating systems):
    - » Signaler keeps lock and processor
    - » Waiter placed on ready queue with no special priority
    - » Practically, need to check condition again after wait

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## Administrivia

- First design document due *tonight*
  - Has to be in by 11:59pm
  - Good luck!
- What we expect in document/review:
  - Architecture, correctness constraints, algorithms, pseudocode, NO CODE!
  - Important: testing strategy, and test case types
- Design reviews:
  - Everyone must attend! (no exceptions)
  - 2 points off for one missing person
  - 1 additional point off for each additional missing person
  - Penalty for arriving late (plan on arriving 5–10 mins early)
  - Please sign up by today (signup link off announcements)

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## Administrivia (con't)

- Yes, there will be design reviews tomorrow
  - If there is a slot and you are signed up for it, there will be a design review tomorrow
  - I realize that there is a teach-in/walk out
- Why will there be protests tomorrow?
  - State drastically cut funding (200 Million)
  - Administration cut pay (roughly 8% for many)
  - Expectation that there will be no reduction in quality/quantity of teaching (Hmmm!)
- Effectively, there is an unsustainable situation on the part of public funding
  - Voters seem to think (or Sacramento, or ..) that the University of California can run with less money and keep the quality up (yeah, right!)
  - Not clear how to fix it, other than with publicity

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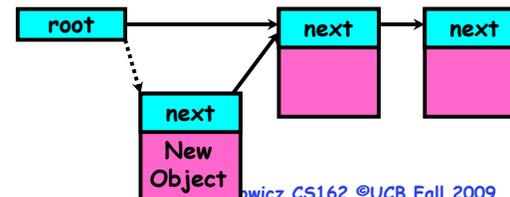
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## Using of Compare&Swap for queues

```
compare&swap (&address, reg1, reg2) { /* 68000 */
 if (reg1 == M[address]) {
 M[address] = reg2;
 return success;
 } else {
 return failure;
 }
}
```

Here is an atomic add to linked-list function:

```
addToQueue(&object) {
 do {
 // repeat until no conflict
 ld r1, M[root] // Get ptr to current head
 st r1, M[object] // Save link in new object
 } until (compare&swap(&root,r1,object));
}
```

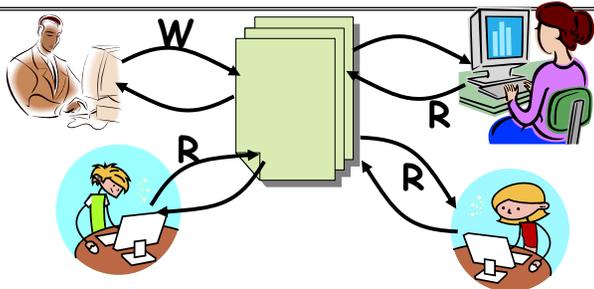


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## Readers/Writers Problem



- **Motivation: Consider a shared database**
  - **Two classes of users:**
    - » Readers - never modify database
    - » Writers - read and modify database
  - **Is using a single lock on the whole database sufficient?**
    - » Like to have many readers at the same time
    - » Only one writer at a time

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## Basic Readers/Writers Solution

- **Correctness Constraints:**
  - Readers can access database when no writers
  - Writers can access database when no readers or writers
  - Only one thread manipulates state variables at a time
- **Basic structure of a solution:**
  - Reader()
    - Wait until no writers
    - Access data base
    - Check out - wake up a waiting writer
  - Writer()
    - Wait until no active readers or writers
    - Access database
    - Check out - wake up waiting readers or writer
  - **State variables (Protected by a lock called "lock"):**
    - » int AR: Number of active readers; initially = 0
    - » int WR: Number of waiting readers; initially = 0
    - » int AW: Number of active writers; initially = 0
    - » int WW: Number of waiting writers; initially = 0
    - » Condition okToRead = NIL
    - » Condition okToWrite = NIL

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## Code for a Reader

```
Reader() {
 // First check self into system
 lock.Acquire();
 while ((AW + WW) > 0) { // Is it safe to read?
 WR++; // No. Writers exist
 okToRead.wait(&lock); // Sleep on cond var
 WR--; // No longer waiting
 }
 AR++; // Now we are active!
 lock.release();
 // Perform actual read-only access
 AccessDatabase(ReadOnly);
 // Now, check out of system
 lock.Acquire();
 AR--; // No longer active
 if (AR == 0 && WW > 0) // No other active readers
 okToWrite.signal(); // Wake up one writer
 lock.Release();
}
```

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## Code for a Writer

```
Writer() {
 // First check self into system
 lock.Acquire();
 while ((AW + AR) > 0) { // Is it safe to write?
 WW++; // No. Active users exist
 okToWrite.wait(&lock); // Sleep on cond var
 WW--; // No longer waiting
 }
 AW++; // Now we are active!
 lock.release();
 // Perform actual read/write access
 AccessDatabase(ReadWrite);
 // Now, check out of system
 lock.Acquire();
 AW--; // No longer active
 if (WW > 0){ // Give priority to writers
 okToWrite.signal(); // Wake up one writer
 } else if (WR > 0) { // Otherwise, wake reader
 okToRead.broadcast(); // Wake all readers
 }
 lock.Release();
}
```

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## Simulation of Readers/Writers solution

- Consider the following sequence of operators:
  - R1, R2, W1, R3
- On entry, each reader checks the following:

```
while ((AW + WW) > 0) { // Is it safe to read?
 WR++; // No. Writers exist
 okToRead.wait(&lock); // Sleep on cond var
 WR--; // No longer waiting
}
AR++; // Now we are active!
```
- First, R1 comes along:  
AR = 1, WR = 0, AW = 0, WW = 0
- Next, R2 comes along:  
AR = 2, WR = 0, AW = 0, WW = 0
- Now, readers make take a while to access database
  - Situation: Locks released
  - Only AR is non-zero

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## Simulation(2)

- Next, W1 comes along:

```
while ((AW + AR) > 0) { // Is it safe to write?
 WW++; // No. Active users exist
 okToWrite.wait(&lock); // Sleep on cond var
 WW--; // No longer waiting
}
AW++;
```
- Can't start because of readers, so go to sleep:  
AR = 2, WR = 0, AW = 0, WW = 1
- Finally, R3 comes along:  
AR = 2, WR = 1, AW = 0, WW = 1
- Now, say that R2 finishes before R1:  
AR = 1, WR = 1, AW = 0, WW = 1
- Finally, last of first two readers (R1) finishes and wakes up writer:

```
if (AR == 0 && WW > 0) // No other active readers
 okToWrite.signal(); // Wake up one writer
```

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## Simulation(3)

- When writer wakes up, get:  
AR = 0, WR = 1, AW = 1, WW = 0
- Then, when writer finishes:

```
if (WW > 0) { // Give priority to writers
 okToWrite.signal(); // Wake up one writer
} else if (WR > 0) { // Otherwise, wake reader
 okToRead.broadcast(); // Wake all readers
}
```
- Writer wakes up reader, so get:  
AR = 1, WR = 0, AW = 0, WW = 0
- When reader completes, we are finished

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## Questions

- Can readers starve? Consider Reader() entry code:

```
while ((AW + WW) > 0) { // Is it safe to read?
 WR++; // No. Writers exist
 okToRead.wait(&lock); // Sleep on cond var
 WR--; // No longer waiting
}
AR++; // Now we are active!
```
- What if we erase the condition check in Reader exit?

```
AR--; // No longer active
if (AR == 0 && WW > 0) // No other active readers
 okToWrite.signal(); // Wake up one writer
```
- Further, what if we turn the signal() into broadcast()

```
AR--; // No longer active
okToWrite.broadcast(); // Wake up one writer
```
- Finally, what if we use only one condition variable (call it "okToContinue") instead of two separate ones?
  - Both readers and writers sleep on this variable
  - Must use broadcast() instead of signal()

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## Can we construct Monitors from Semaphores?

- Locking aspect is easy: Just use a mutex
- Can we implement condition variables this way?

```
Wait() { semaphore.P(); }
Signal() { semaphore.V(); }
```

- Does this work better?

```
Wait(Lock lock) {
 lock.Release();
 semaphore.P();
 lock.Acquire();
}
Signal() { semaphore.V(); }
```

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## Construction of Monitors from Semaphores (con't)

- Problem with previous try:
  - P and V are commutative - result is the same no matter what order they occur
  - Condition variables are NOT commutative
- Does this fix the problem?
 

```
Wait(Lock lock) {
 lock.Release();
 semaphore.P();
 lock.Acquire();
}
Signal() {
 if semaphore queue is not empty
 semaphore.V();
}
```

  - Not legal to look at contents of semaphore queue
  - There is a race condition - signaler can slip in after lock release and before waiter executes semaphore.P()
- It is actually possible to do this correctly
  - Complex solution for Hoare scheduling in book
  - Can you come up with simpler Mesa-scheduled solution?

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## Monitor Conclusion

- Monitors represent the logic of the program
  - Wait if necessary
  - Signal when change something so any waiting threads can proceed

- Basic structure of monitor-based program:

```
lock
while (need to wait) { }
unlock
```

Check and/or update state variables  
Wait if necessary

do something so no need to wait

```
lock
condvar.signal();
unlock
```

Check and/or update state variables

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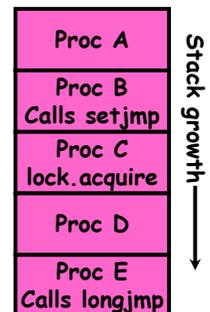
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## C-Language Support for Synchronization

- C language: Pretty straightforward synchronization
  - Just make sure you know *all* the code paths out of a critical section

```
int Rtn() {
 lock.acquire();
 ...
 if (exception) {
 lock.release();
 return errReturnCode;
 }
 ...
 lock.release();
 return OK;
}
```



- Watch out for setjmp/longjmp!
  - » Can cause a non-local jump out of procedure
  - » In example, procedure E calls longjmp, popping stack back to procedure B
  - » If Procedure C had lock.acquire, problem!

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## C++ Language Support for Synchronization

- Languages with exceptions like C++
  - Languages that support exceptions are problematic (easy to make a non-local exit without releasing lock)
  - Consider:

```
void Rtn() {
 lock.acquire();
 ...
 DoFoo();
 ...
 lock.release();
}
void DoFoo() {
 ...
 if (exception) throw errException;
 ...
}
```
  - Notice that an exception in DoFoo() will exit without releasing the lock

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## C++ Language Support for Synchronization (con't)

- Must catch all exceptions in critical sections
  - Catch exceptions, release lock, and re-throw exception:

```
void Rtn() {
 lock.acquire();
 try {
 ...
 DoFoo();
 ...
 } catch (...) { // catch exception
 lock.release(); // release lock
 throw; // re-throw the exception
 }
 lock.release();
}
void DoFoo() {
 ...
 if (exception) throw errException;
 ...
}
```
  - Even Better: auto\_ptr<T> facility. See C++ Spec.  
» Can deallocate/free lock regardless of exit method

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## Java Language Support for Synchronization

- Java has explicit support for threads and thread synchronization
- Bank Account example:

```
class Account {
 private int balance;
 // object constructor
 public Account (int initialBalance) {
 balance = initialBalance;
 }
 public synchronized int getBalance() {
 return balance;
 }
 public synchronized void deposit(int amount) {
 balance += amount;
 }
}
```
- Every object has an associated lock which gets automatically acquired and released on entry and exit from a *synchronized* method.

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## Java Language Support for Synchronization (con't)

- Java also has *synchronized* statements:

```
synchronized (object) {
 ...
}
```
- Since every Java object has an associated lock, this type of statement acquires and releases the object's lock on entry and exit of the body
- Works properly even with exceptions:

```
synchronized (object) {
 ...
 DoFoo();
 ...
}
void DoFoo() {
 throw errException;
}
```

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## Java Language Support for Synchronization (con't 2)

- In addition to a lock, every object has a **single** condition variable associated with it
  - How to wait inside a synchronization method or block:
    - » `void wait(long timeout); // Wait for timeout`
    - » `void wait(long timeout, int nanoseconds); //variant`
    - » `void wait();`
  - How to signal in a synchronized method or block:
    - » `void notify(); // wakes up oldest waiter`
    - » `void notifyAll(); // like broadcast, wakes everyone`
  - Condition variables can wait for a bounded length of time. This is useful for handling exception cases:

```
t1 = time.now();
while (!ATMRequest()) {
 wait (CHECKPERIOD);
 t2 = time.now();
 if (t2 - t1 > LONG_TIME) checkMachine();
}
```
  - Not all Java VMs equivalent!
    - » Different scheduling policies, not necessarily preemptive!

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## Summary

- **Semaphores**: Like integers with restricted interface
  - Two operations:
    - » **P()**: Wait if zero; decrement when becomes non-zero
    - » **V()**: Increment and wake a sleeping task (if exists)
    - » Can initialize value to any non-negative value
  - Use separate semaphore for each constraint
- **Monitors**: A lock plus one or more condition variables
  - Always acquire lock before accessing shared data
  - Use condition variables to wait inside critical section
    - » Three Operations: **Wait()**, **Signal()**, and **Broadcast()**
- **Readers/Writers**
  - Readers can access database when no writers
  - Writers can access database when no readers
  - Only one thread manipulates state variables at a time
- Language support for synchronization:
  - Java provides **synchronized** keyword and one condition-variable per object (with **wait()** and **notify()**)

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