Practical Concurrent and Parallel Programming 7

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Plan for today

- **Threadsafe long integers with ”striping”**
- Memory, cache and cache coherence
  - Shared mutable data on multicore is slow
- Graphical user interface toolkits, eg Swing
  - not thread-safe, access from event thread only
- Using SwingWorker for long-running work
  - Progress bar
  - Cancellation
  - Display results as they are generated
- A thread-based lift simulator with GUI

Based on slides by Peter Sestoft

Flashback week 6: Maintaining hashmap size information

- Using a single AtomicLong limits scalability
- We used one size component per stripe:

```
class StripedMap<K,V> implements OurMap<K,V> {
  private final int[] sizes;
  public int size() {
    ... for-loop summing sizes[i] ...
  }
  ...
}
```

- Fast updates but slow **`size()`** queries
  - *Very slow* if millions of stripes, as in Java 8 CHM
- Java 8 ConcurrentHashMap uses a LongAdder
  - A **`long`** counter that scales well with many threads
  - If there are more writes (**`add`**) than reads (**`get`**)

Thread-safe longs: simple, striped, …

- Vastly different scalability
  - (a) Java 5's AtomicLong
  - (b) Home-made single-lock LongCounter (week 1)
  - (c) Home-made striped long using AtomicLongArray
  - (d) Home-made striped long using AtomicLong[]
  - (e) Home-made striped long with scattered allocation
  - (f) Java 8's LongAdder

TestLongAdders.java

- Ideas
  - (c,d,e) Use thread's hashCode to reduce update collisions
  - (e) Scatter AtomicLongs to avoid false cache line sharing
  - Difference d-e is scattering of AtomicLong objects in memory

	i7 4c	AMD 32c	Xeon 48c
(a)	974	3011	667
(b)	499	14921	815
(c)	422	1611	956
(d)	183	-	296
(e)	114	922	135
(f)	64	54	22

Wall clock time (ms) for 32 threads making 1 million additions each

(d)

Dividing a long into 31 "stripes"

TestLongAdders.java

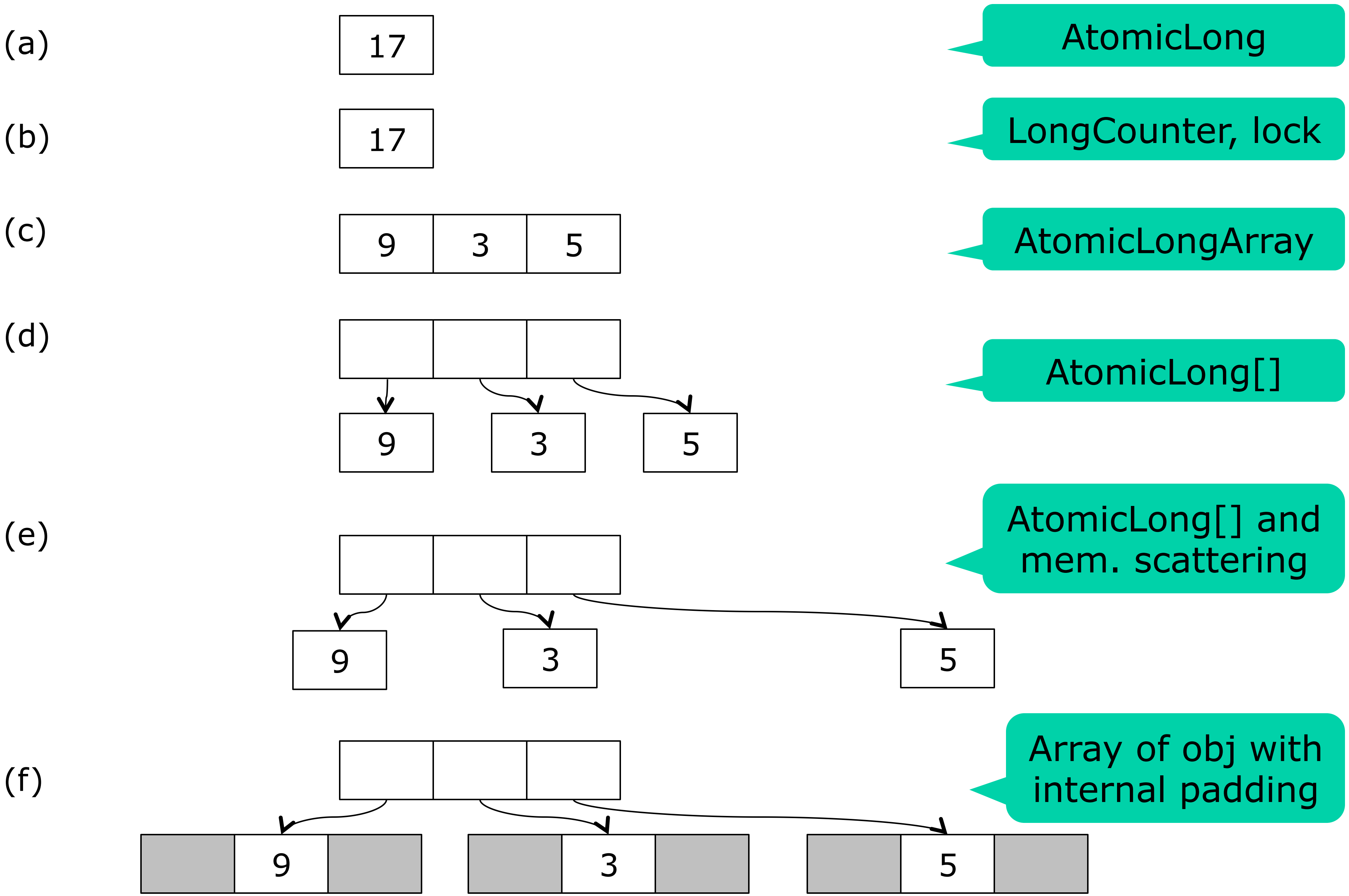
```
class NewLongAdder {
  private final static int NSTRIPES = 31;
  private final AtomicLong[] counters;
  ...
  public void add(long delta) {
    counters[Thread.currentThread().hashCode() % NSTRIPES].addAndGet(delta);
  }

  public long longValue() {
    long result = 0;
    for (int stripe=0; stripe<NSTRIPES; stripe++)
      result += counters[stripe].get();
    return result;
  }
}
```

Thread's hashcode selects stripe

- Two threads unlikely to add to same stripe
- Each thread has a home stripe – "affinity"
  - if accessed by thread, likely to be accessed again
- So, quite fast despite the cost of **`hashCode()`**

The long adders' memory layouts



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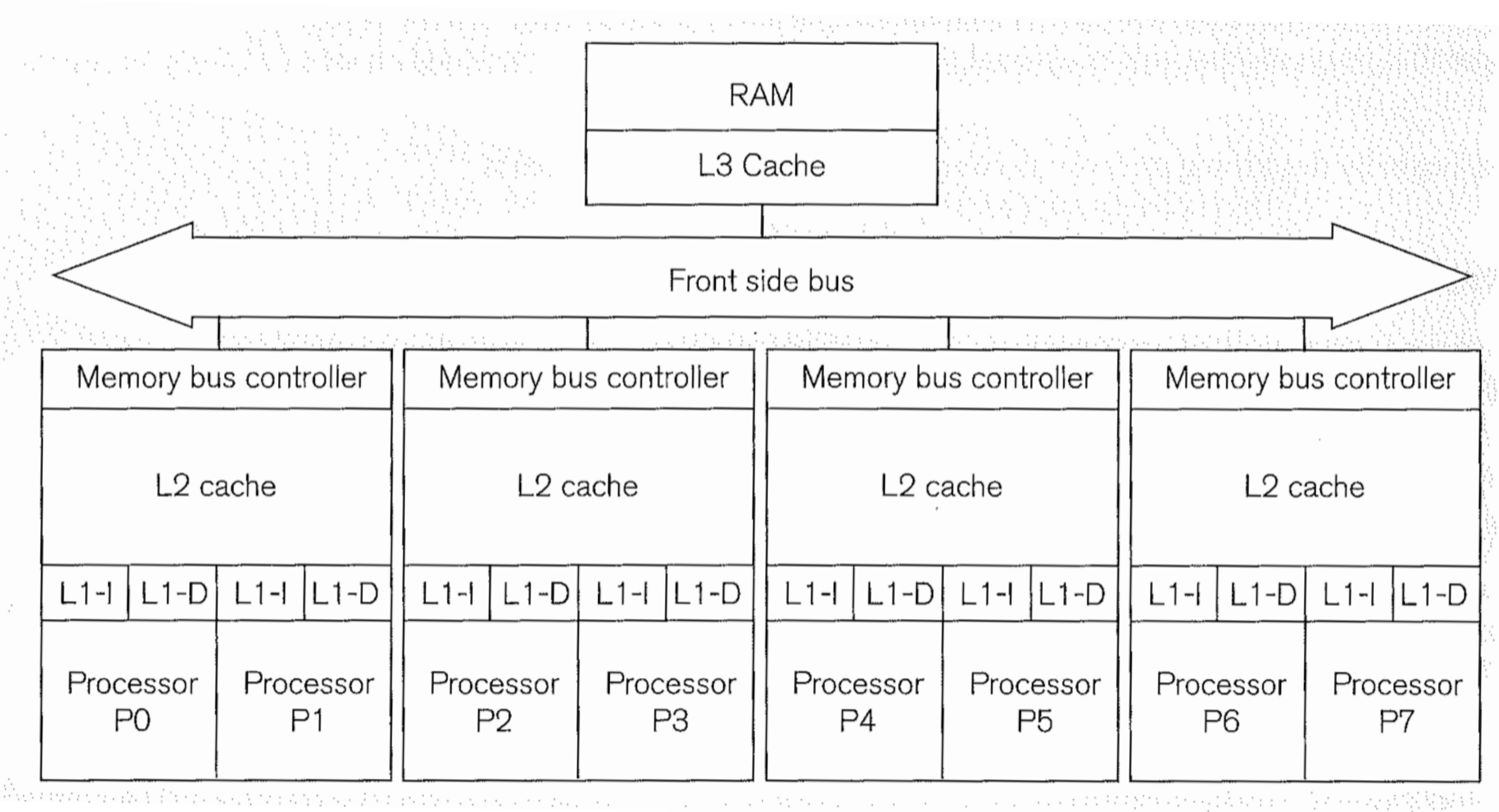
A typical multicore CPU with three levels of cache

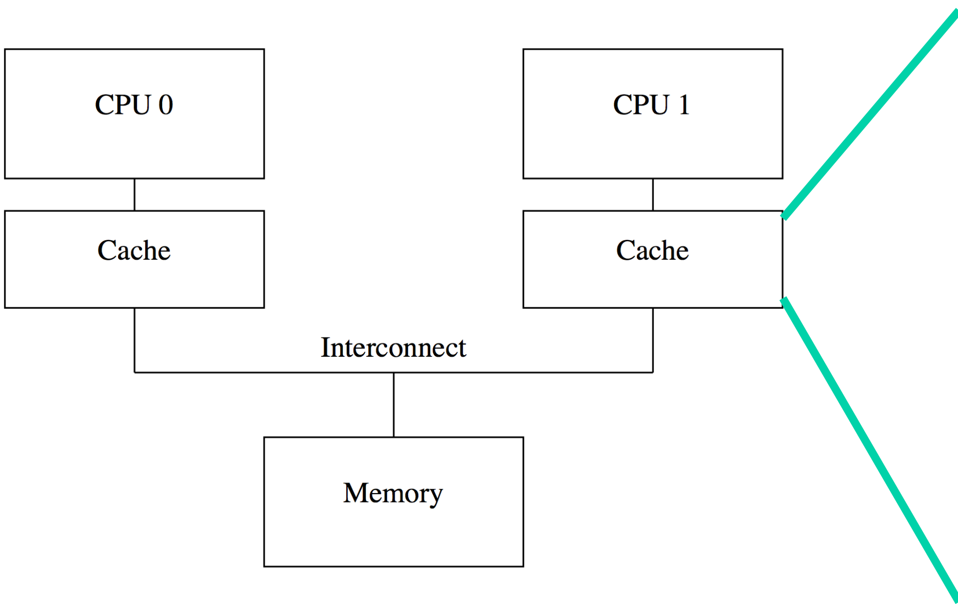


Lin & Snyder 2009, p. 16

- Floating-point register add or mul: 0.4 ns
- RAM access: > 80 ns (single-thread read)

Fix 1: Each processor core has a cache

- Cache = simple hardware hashtable
- Stores recently accessed values from RAM
- Cache is much faster than RAM



A cache line

	Way 0	Way 1
0x0	0x12345000	
0x1	0x12345100	
0x2	0x12345200	
0x3	0x12345300	
0x4	0x12345400	
0x5	0x12345500	
0x6	0x12345600	
0x7	0x12345700	
0x8	0x12345800	
0x9	0x12345900	
0xA	0x12345A00	
0xB	0x12345B00	
0xC	0x12345C00	
0xD	0x12345D00	
0xE	0x12345E00	0x43210E00
0xF		

McKenney 2010: Memory barriers

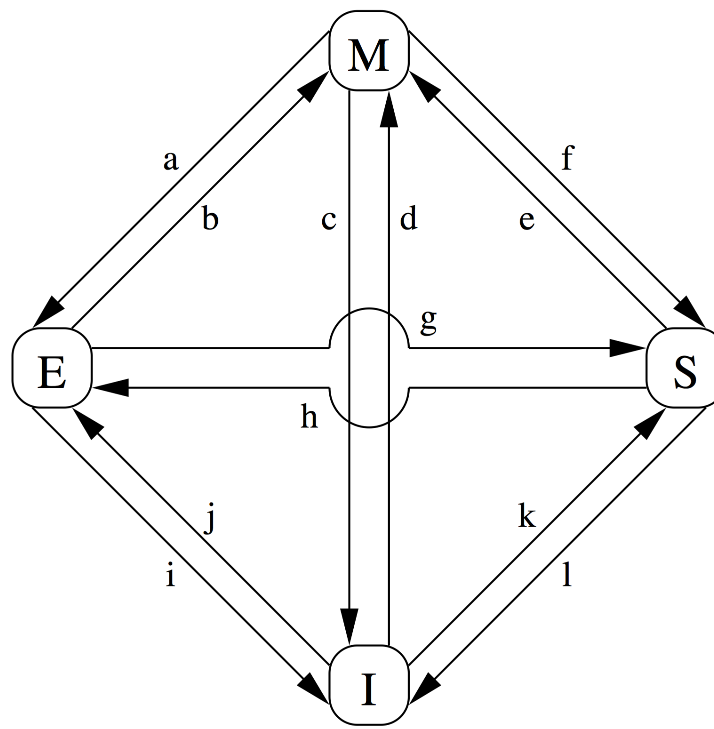
- Two caches may have different values for a given memory address

Fix 2: Get all caches to agree

- Cache coherence; cache line state = M,E,S,I

State	Cache line	Excl	RAM	To read	To write
Modified	Modified by me	Y	stale	from cache	to cache
Exclusive	Not modified	Y	fresh	from cache	to cache -> M
Shared	Others have it too	N	fresh	from cache	send invalidate
Invalid	Not in use by me	-	-	elsewhere	send invalidate

- A cache line
  - has 4 possible states
  - and 12 transitions a-l
- Cache messages
  - sent by cores to others
  - via cache bus
  - to make caches agree

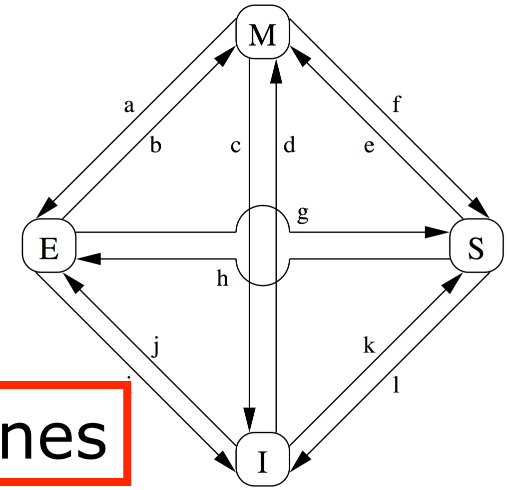


McKenney 2010: Memory barriers

Transitions and messages

A write in a non-exclusive state requires acknowledge ack* from *all other* cores

Shared mutable state is slow on big machines



		Cause	I send	I receive	My response
M	a	(Send update to RAM)	writeback	-	-
E	b	Write	-	-	-
M	c	Other wants to write	-	read inv	read resp, inv ack
I	d	Atomic read-mod-write	read inv	read resp, inv ack*	-
S	e	Atomic read-mod-write	read inv	inv ack*	-
M	f	Other wants to read	-	read	read resp
E	g	Other wants to read	-	read	read resp
S	h	Will soon write	inv	inv ack*	-
E	i	Other wants atomic rw	-	read inv	read resp, inv ack
I	j	Want to write	read inv	read resp, inv ack*	-
I	k	Want to read	read	read resp	-
S	l	Other wants to write	-	inv	inv ack

Fast and slow cache cases

- The cache is **fast** when
  - the local core “owns” the data (state M or E), or
  - data is shared (S) but local core *only reads* it
- The cache is **slow** when
  - the data is shared (S) and we want to write it, or
  - the data is not in cache (I)
    - possibly because cache line “owned” by another core

		This core wants to	Messages	Speed
M	M	Read cache line	0	fast
M	M	Write cache line	0	fast
E	E	Read cache line	0	fast
E	M	Write cache line	0	fast
S	S	Read cache line	0	fast
I	S	Read cache line	1+1	slow
S	M	Write cache line	1+N	very slow
I	M	Write cache line	1+1+N	very slow

Unshared mutable

Shared immutable

Shared mutable

N cores

One more performance problem: "false sharing" because of cache lines

- A cache line typically is 64 bytes
  - gives better memory bus utilization
  - prefetches data (in array) that may be needed next
- Thus invalidating one (8 byte) long may invalidate the neighboring 7 longs!
- Frequently written memory locations should not be on the same cache line!
  - even if apparently not shared between threads
- Attempts to fix this by "padding"
  - may look very silly (next slide)
  - are not guaranteed to help
  - yet are used in the Java class library code

Scattering the stripes of a long

```
class NewLongAdderPadded {
  private final static int NSTRIPES = 31;
  private final AtomicLong[] counters;

  public NewLongAdderPadded() {
    this.counters = new AtomicLong[NSTRIPES];
    for (int stripe=0; stripe<NSTRIPES; stripe++) {
      // Believe it or not, this sometimes speeds up the code,
      // presumably because avoids false sharing of cache lines:
      new Object(); new Object(); new Object(); new Object();
      counters[stripe] = new AtomicLong();
    }
  }
}
```

TestLongAdders.java

Avoid side-by-side AtomicLong allocation

- Allocate many AtomicLongs
  - instead of AtomicLongArray
- Scatter the AtomicLongs
  - by allocating some Objects in between

Unless JVM is too clever

Don't do this at home

Plan for today

- Atomic longs with ”striping” (week 6)
- Memory, cache and cache coherence
  - Shared mutable data on multicore is slow
- **Graphical user interface toolkits, Swing**
  - not thread-safe, access from event thread only
- Using SwingWorker for long-running work
  - Progress bar
  - Cancellation
  - Display results as they are generated
- A thread-based lift simulator with GUI

GUI toolkits are single-threaded

- Java Swing components are **not** thread-safe
  - This is intentional
  - Ditto .NET's System.Windows.Forms and others
- Multithreaded GUI toolkits
  - are difficult to use
  - deadlock-prone, because actions are initiated both
    - *top-down*: from user towards operating system
    - *bottom-up*: from operating system to user interface
    - locking in different orders ... hence deadlock risk
- In Swing, at least two threads:
  - Main Thread – runs **`main(String[] args)`**
  - Event Thread – runs ActionListeners and so on

Lock Ordering

- Two threads: 1,2
- Two locks: A,B
- Thread 1: acquire first lock A, then lock B
- Thread 2: acquire first lock B, then lock A
- If both manage to acquire ‘their’ first lock, both get stuck: **DEADLOCK**

- If there is a global total order of all locks and all threads acquire locks in this order, the above cannot happen.

From Graham Hamilton's blog post
"Multithreaded toolkits: A failed dream?"

- *"In general, GUI operations start at the top of a stack of library abstractions and go "down". I am operating on an abstract idea in my application that is expressed by some GUI objects, so I start off in my application and call into high-level GUI abstractions, that call into lower level GUI abstractions, that call into the ugly guts of the toolkit, and thence into the OS.*
- *In contrast, input events start off at the OS layer and are progressively dispatched "up" the abstraction layers, until they arrive in my application code.*
- *Now, since we are using abstractions, we will naturally be doing locking separately within each abstraction.*
- *And unfortunately we have the classic lock ordering nightmare: we have two different kinds of activities going on that want to acquire locks in opposite orders. So deadlock is almost inevitable."* (19 October 2004)

https://weblogs.java.net/blog/kgh/archive/2004/10/multithreaded_t.html

Java Swing GUI toolkit dogmas

- Dogma 1: “Time-consuming tasks should **not** be run on the Event Thread”
  - Otherwise the application becomes unresponsive
- Dogma 2: “Swing components should be accessed on the Event Thread only”
  - The components are not thread-safe
- But if another thread does long-running work, how can it show the results on the GUI?
  - Define the work in SwingWorker subclass instance
  - Use **`execute()`** to run it on a worker thread
  - The Event Thread can pick up the results

javax.swing.SwingWorker documentation

A short computation on the event thread

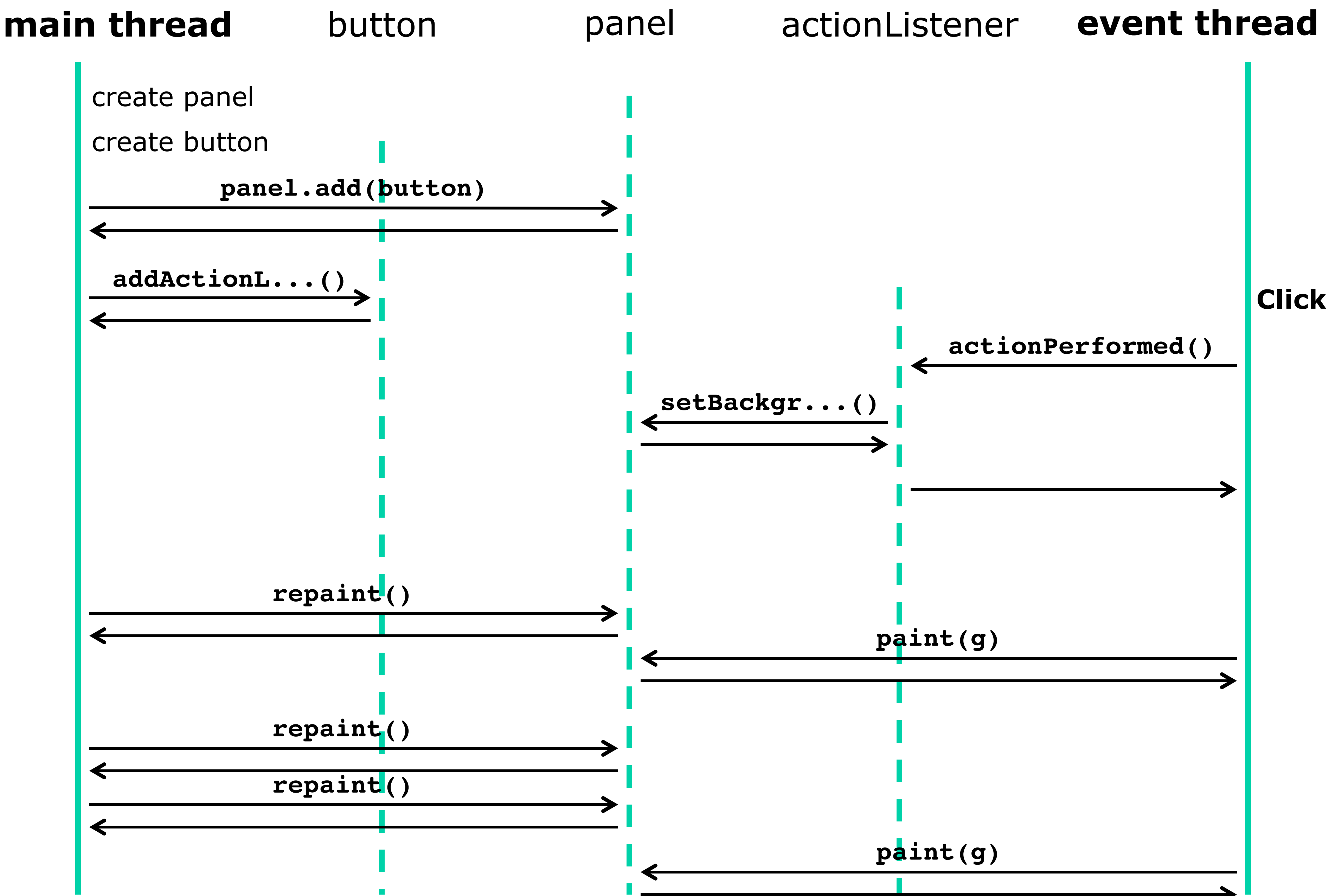
B 1

TestButtonGui.java

```
final JFrame frame = new JFrame("TestButtonGui");
final JPanel panel = new JPanel();
final JButton button = new JButton("Press here");
frame.add(panel);
panel.add(button);
button.addActionListener(new ActionListener() {
    public void actionPerformed(ActionEvent e) {
      panel.setBackground(new Color(random.nextInt()));
    }});
frame.pack(); frame.setVisible(true);
```

- Main thread may create GUI components
  - But should not change eg. background color later
- Event thread calls the ActionListener
  - And can change the background color

Main thread and event thread



Using the main thread for blinking


```
final JPanel panel = new JPanel() {
    public void paint(Graphics g) {
      super.paint(g);
      if (showBar) {
        g.setColor(Color.RED);
        g.fillRect(0, 0, 10, getHeight());
} }  };
final JButton button = ...
frame.pack(); frame.setVisible(true);
while (true) {
  try { Thread.sleep(800); } // milliseconds
  catch (InterruptedException exn) { }
  showBar = !showBar;
  panel.repaint();
}
```

- **`repaint()`** may be called by any thread
- Causes event thread to call **`paint(g)`** later

Fetching webpages on event thread

W 0

```
fetchButton.addActionListener(new ActionListener() {
  public void actionPerformed(ActionEvent e) {
    for (String url : urls) {
      System.out.println("Fetching " + url);
      String page = getPage(url, 200);
      textArea.append(String.format(..., url, page.length()));
    }
}});
```

On event thread

TestFetchWebGui.java

Bad

- Occupies event thread for many seconds
  - The GUI is unresponsive in the meantime
  - Results not shown as they become available
    - GUI gets updated only after *all* fetches
  - Cancellation would not work
    - Cancel button event processed only after *all* fetches
  - A progress bar would not work
    - Gets updated only after *all* fetches

Fetching web with SwingWorker

```
static class DownloadWorker extends SwingWorker<String,String> {
  private final TextArea textArea;
  public String doInBackground() {
    StringBuilder sb = new StringBuilder();
    for (String url : urls) {
      String page = getPage(url, 200),
        result = String.format("%-40s%7d%n", url, page.length());
      sb.append(result);
    }
    return sb.toString();
  }

  public void done() {
    try { textArea.append(get()); }
    catch (InterruptedException exn) { }
    catch (ExecutionException exn) { throw new RuntimeExc...; }
  }
}
```

On worker thread

Computed result

Get result

On event thread

TestFetchWebGui.java

- SwingWorker<T,V> implements Future<T>
- .NET has similar System.ComponentModel.BackgroundWorker

Fetching web with SwingWorker

TestFecthWebGui.java

```
DownloadWorker downloadTask = new DownloadWorker(textArea);
fetchButton.addActionListener(new ActionListener() {
  public void actionPerformed(ActionEvent e) {
    downloadTask.execute();
}});
```

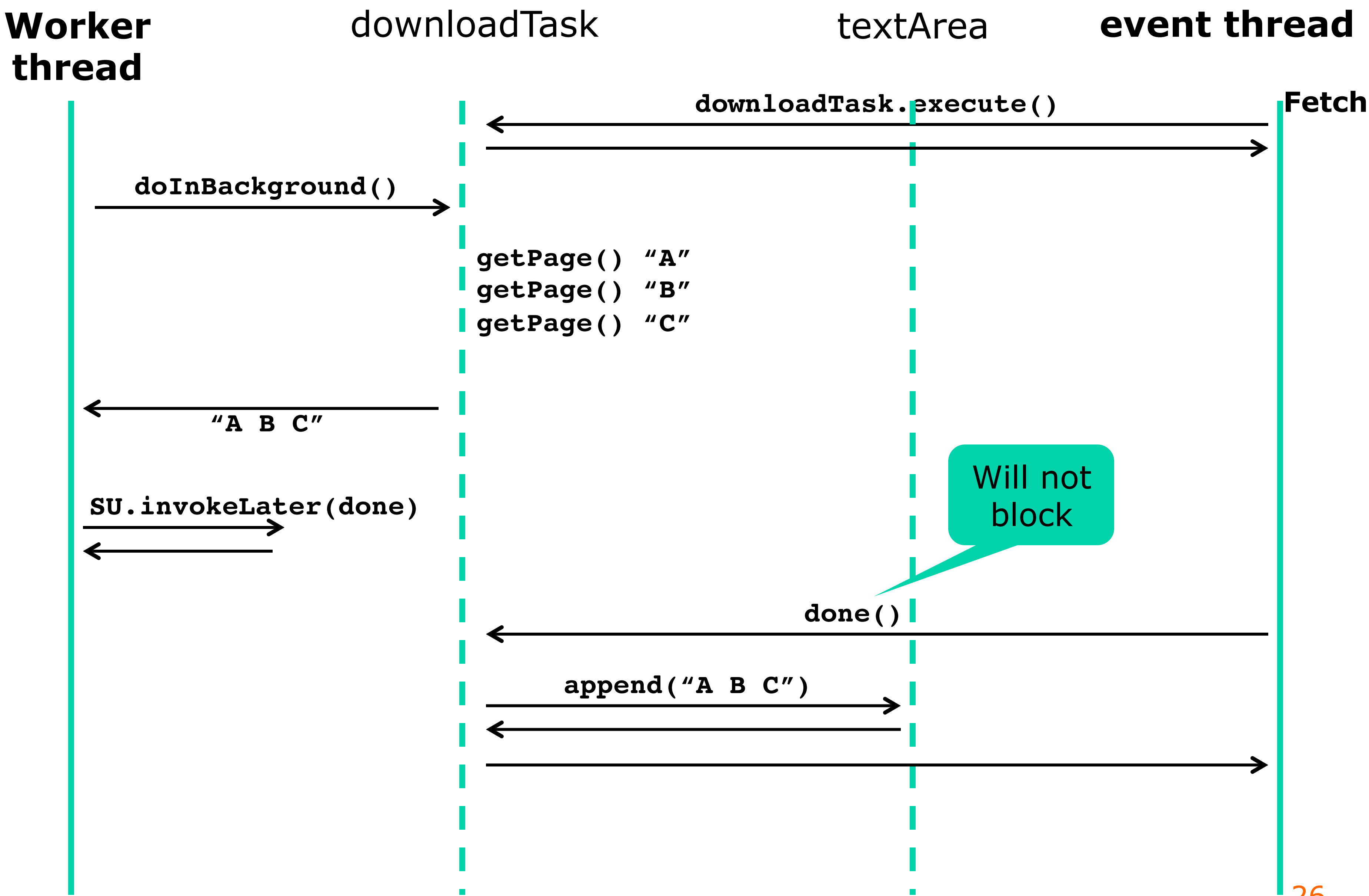
- Event thread runs **`execute()`**
- Worker thread runs **`doInBackground()`**
  - which returns the full result when computed
- Event thread runs **`done()`**
  - obtains the already-computed result with **`get()`**
  - and writes the result to the textArea

Dogma 1

Dogma 2

Worker thread and event thread

W 1



Add progress notification

```
static class DownloadWorker extends SwingWorker<String,String> {
  public String doInBackground() {
    int count = 0;
    StringBuilder sb = new StringBuilder();
    for (String url : urls) {
      String page = getPage(url, 200),
        result = String.format("%-40s%7d%n", url, page.length());
      sb.append(result);
      setProgress((100 * ++count) / urls.length);
    }
    return sb.toString();
  }
}
```

On worker thread

- In the GUI setup, add:

```
downloadTask.addPropertyChangeListener(new PropertyChangeListener() {
  public void propertyChange(PropertyChangeEvent e) {
    if ("progress".equals(e.getPropertyName())) {
      progressBar.setValue((Integer)e.getNewValue());
}}});
```

On event thread

Add cancellation

```
static class DownloadWorker extends SwingWorker<String,String> {
  public String doInBackground() {
    for (String url : urls) {
      if (isCancelled())
        break;
      ...
      sb.append(result);
    }
    return sb.toString();
  }
  public void done() {
    try { textArea.append(get()); }
    catch (InterruptedException exn) { }
    catch (ExecutionException exn) { throw new RuntimeExc...; }
    catch (CancellationException exn) { textArea.append("Yrk"); }
} }
```

On worker thread

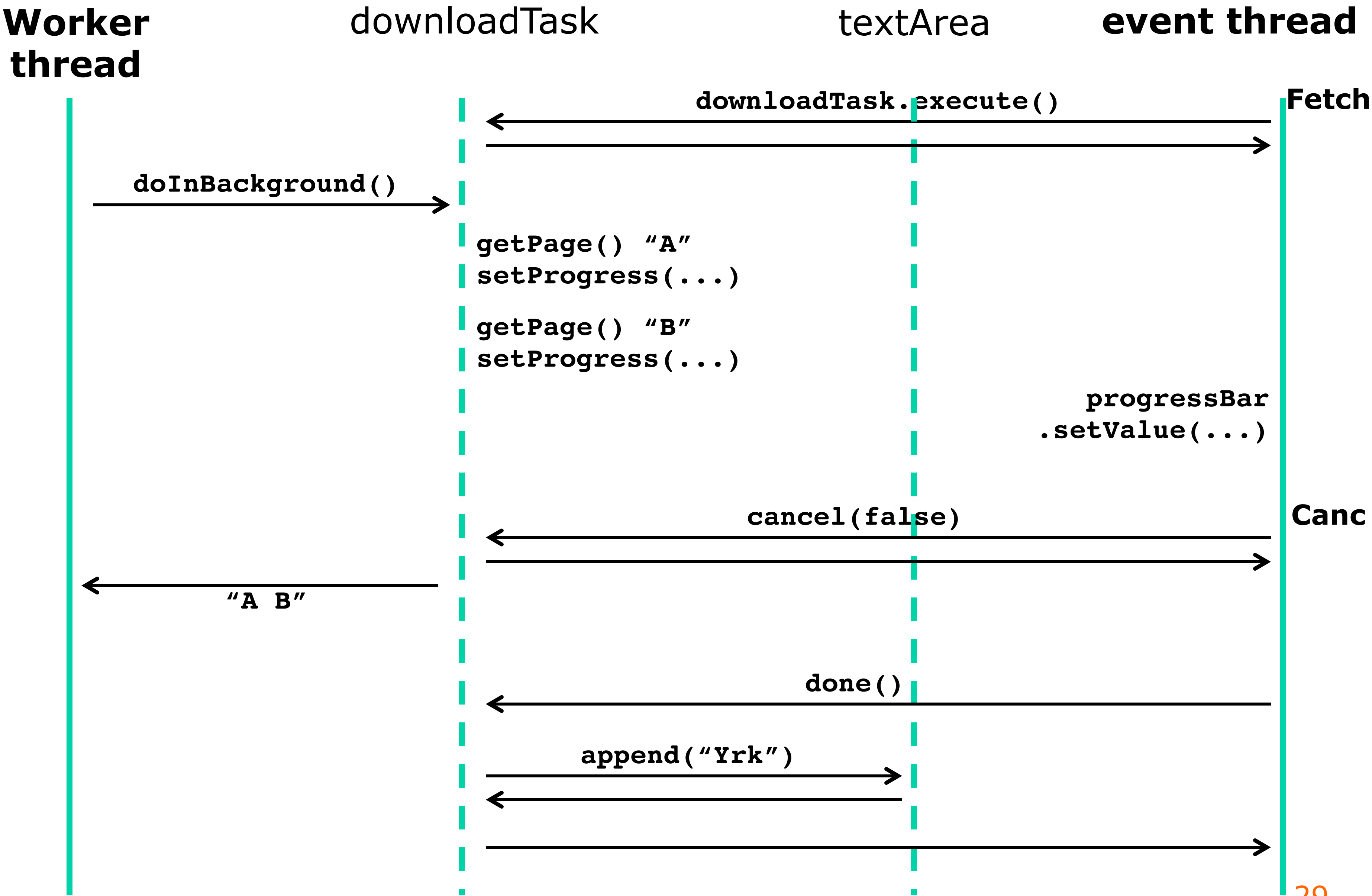
- In the GUI setup, add:

```
cancelButton.addActionListener(new ActionListener() {
  public void actionPerformed(ActionEvent e) {
    downloadTask.cancel(false);
}});
```

On event thread

Progress and cancellation

W 3



Show results gradually

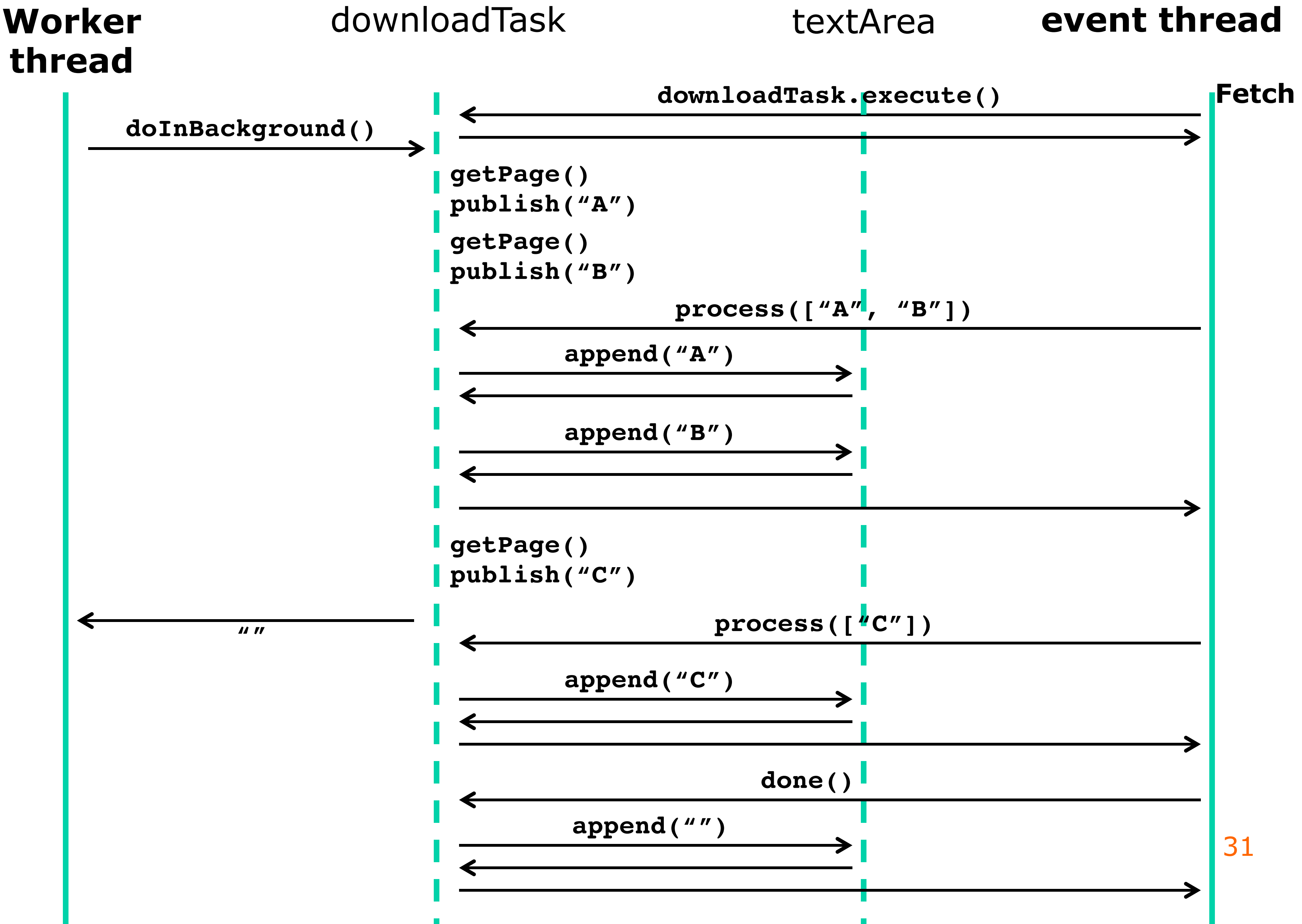
```java
static class DownloadWorker extends SwingWorker<String,String> {
  public String doInBackground() {
    for (String url : urls) {
      String page = getPage(url, 200),
        result = String.format("%-40s%7d%n", url, page.length());
      publish(result);
    }
  }

  public void process(List<String> results) {
    for (String result : results)
      textArea.append(result);
  }
}
```

On worker thread

On event thread

- Worker thread calls **publish(...)** a few times
- Event thread calls **process** with results from the calls to **publish** since last call to **process**

Event thread and downloadTask



SwingUtilities static methods

- May be called from any thread:
  - **`boolean isEventDispatchThread()`**
    - True if executing thread is the Event Thread
  - **`void invokeLater(Runnable cmd)`**
    - Execute **`cmd.run()`** asynchronously on the Event Thread
  - **`void invokeAndWait(Runnable command)`**
    - Execute **`cmd.run()`** on the Event Thread, wait to complete
- SwingWorker = these + Java executors
  - Goetz Listings 9.2 and 9.7 indicate how
- Other methods that any thread may call:
  - adding and removing listeners on components
    - but the listeners are *called* only on the Event Thread
  - **`comp.repaint()`** and **`comp.revalidate()`**

Very proper GUI creation in Swing

as per http://docs.oracle.com/javase/tutorial/uiswing/concurrency/initial.html

```
public static void main(String[] args) {
  SwingUtilities.invokeLater(new Runnable() {
    public void run() {
      final Random random = new Random();
      final JFrame frame = new JFrame("TestButtonGui");
      final JPanel panel = new JPanel();
      final JButton button = new JButton("Press here");
      frame.add(panel);
      panel.add(button);
      button.addActionListener(new ActionListener() {
          public void actionPerformed(ActionEvent e) {
            panel.setBackground(new Color(random.nextInt()));
          }});
      frame.pack(); frame.setVisible(true);
    }
    });
}
```

TestButtonGuiProper.java

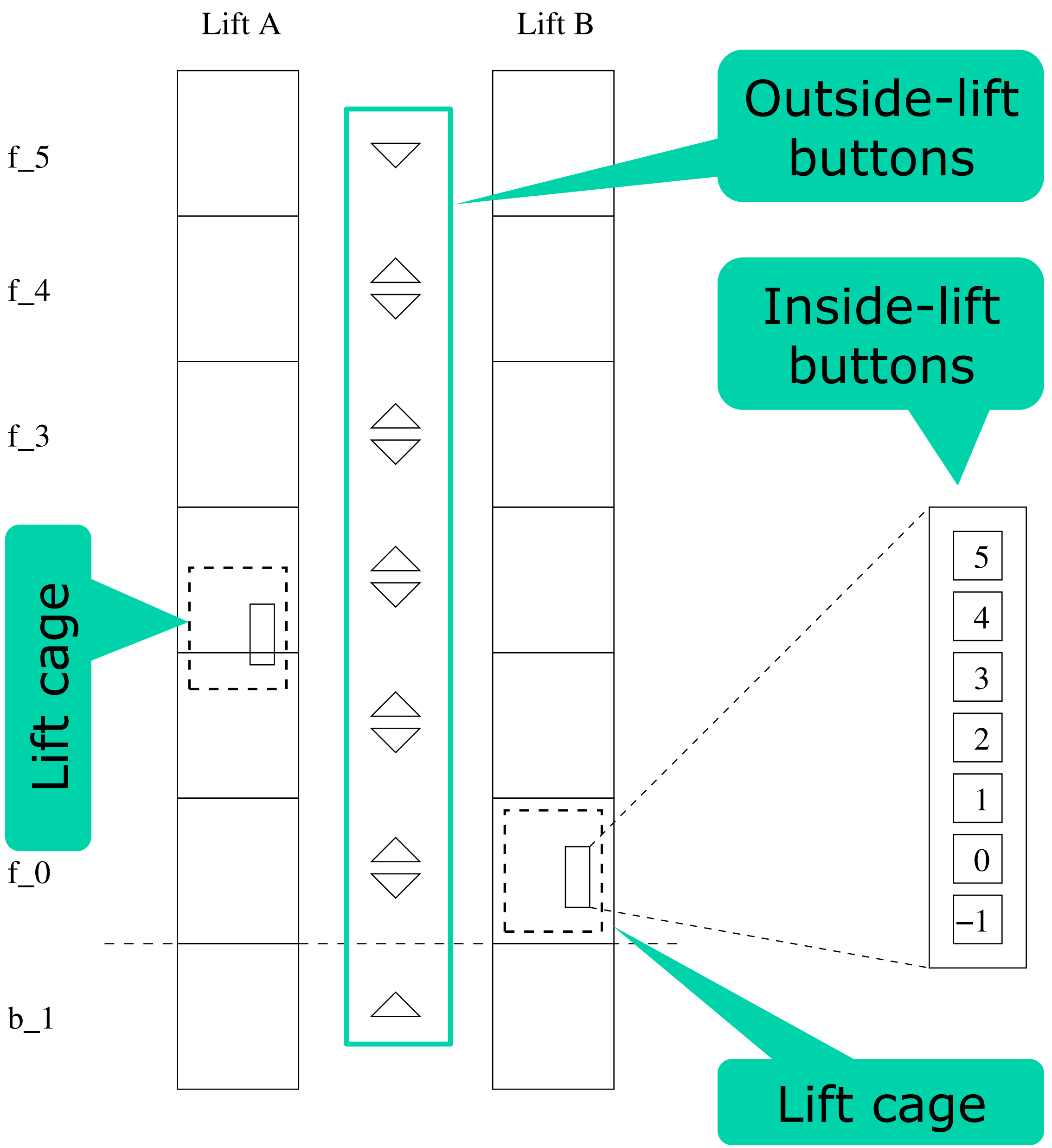
GUI gets built on the Event Thread

- Avoids interaction with a partially constructed GUI
  - because the Event Thread is busy constructing the GUI

Plan for today

- Graphical user interface toolkits, eg Swing
  - not thread-safe, access from event thread only
- Using SwingWorker for long-running work
  - Progress bar
  - Cancellation
  - Display results as they are generated
- **A thread-based lift simulator with GUI**
- Atomic long with ”thread striping” (week 7)
- Shared mutable data on multicore is slow

Example: 2 lifts, 7 floors, 26 buttons



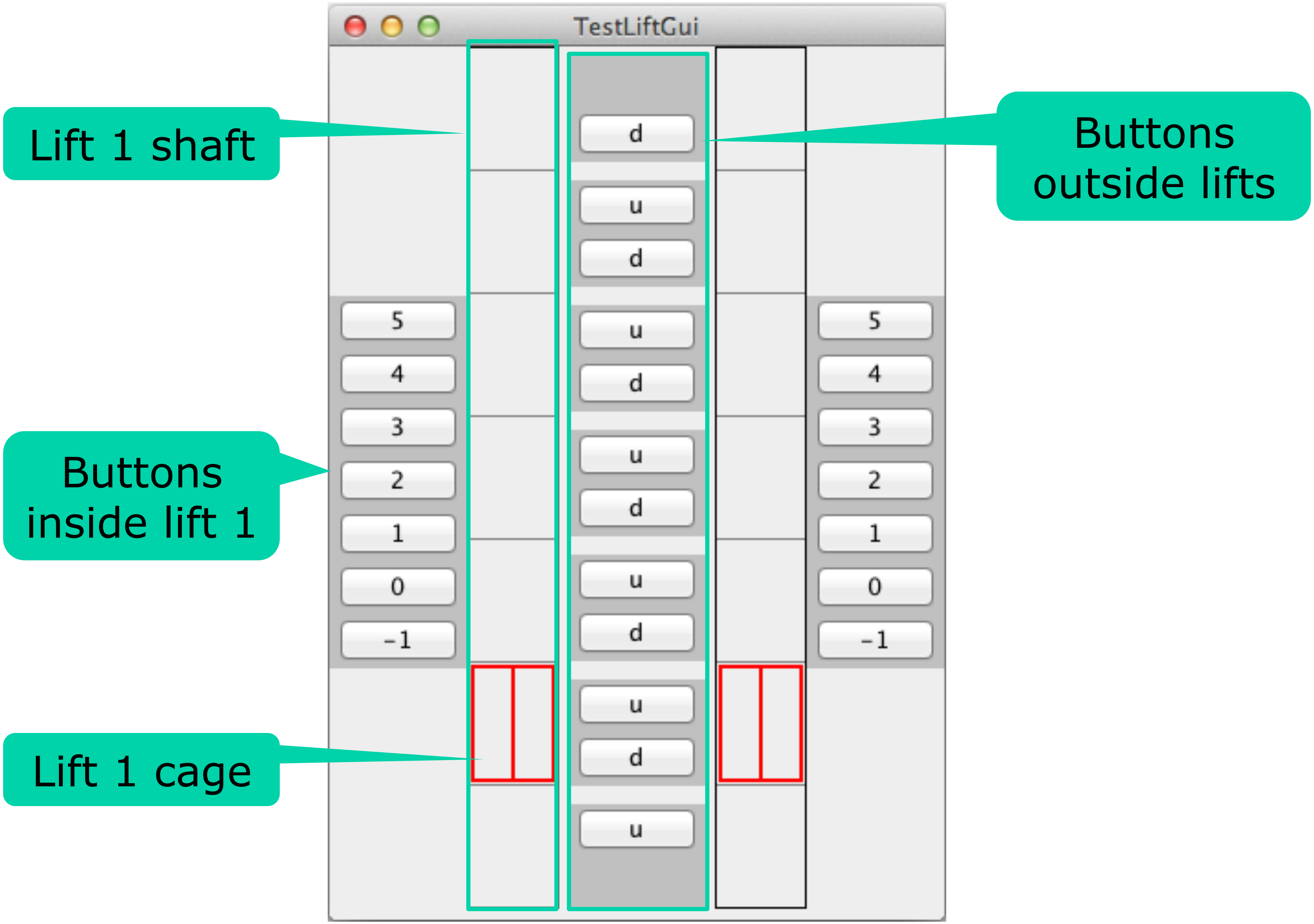
Concurrency:
2 lift cages move
26 buttons pressed

Two lift threads + the event thread

Modeling and visualizing the lifts

- Use event thread for button clicks (obviously)
  - Inside requests: *this lift* must go to floor n
  - Outside requests: *some lift* must go to floor n, and then up (or down)
- An object for each lift
  - to hold current floor, and floors yet to be visited
  - to compute time to serve an outside request
- A thread for each lift
  - to update its state 16 times a second
  - to cause the GUI to display it
- A controller object
  - to decide which lift should serve an outside request

The lift simulator GUI



Lift controller algorithm

- When outside button Up on floor n is pressed
  - Ask each lift how long it would take to get to floor n while continuing up afterwards
  - Then order the fastest lift to serve floor n

```
class LiftController {
  private final Lift[] lifts;
  ...
  public void someLiftTo(int floor, Direction dir) {
    double bestTime = Double.POSITIVE_INFINITY;
    int bestLift = -1;
    for (int i=0; i<lifts.length; i++) {
      double thisLiftTime = lifts[i].timeToServe(floor, dir);
      if (thisLiftTime < bestTime) {
        bestTime = thisLiftTime;
        bestLift = i;
      }
    }
    lifts[bestLift].customerAt(floor, dir);
  }
}
```

Up or Down

Ask lifts[i] how long

Choose the soonest one

TestLiftGui.java

The state of a lift

- Current floor and direction (None, Up, Down)
- required stops and directions, **`stops[n]`**:
  - **`null`**: no need to stop at floor **`n`**
  - **`None`**: stop at floor **`n`**, don't know future direction
  - **`Down`**: stop at floor **`n`**, then continue down
  - **`Up`**: stop at floor **`n`**, then continue up
  - **`Both`**: stop, then up, and later down; or vice versa

```
class Lift implements Runnable {
  private double floor;
  private Direction direction; // None, Up, Down
  // @GuardedBy("this")
  private final Direction[] stops;
  ...
  public synchronized void customerAt(int floor, Direction thenDir) {
    setStop(floor, thenDir.add(getStop(floor)));
  }
}
```

Accessed only on lift thread

Accessed on lift and controller threads

Called by controller

TestLiftGui.java

The lift's behavior when going Up

- If at a floor, check whether to stop here
  - If so, open+close doors and clear from **`stops`** table
- If not yet at highest requested stop
  - move up a bit and refresh display
  - otherwise stop moving

```
switch (direction) {
case Up:
  if ((int)floor == floor) { // At a floor, maybe stop here
    Direction afterStop = getStop((int)floor);
    if (afterStop != null && (afterStop != Down || (int)floor == highestStop())) {
      openAndCloseDoors();
      subtractFromStop((int)floor, direction);
    }
  }
  if (floor < highestStop()) {
    floor += direction.delta / steps;
    shaft.moveTo(floor, 0.0);
  } else
    direction = Direction.None;
  break;
case Down: ... dual to Up ...
case None: ... if any stops[floor] != null, start moving in that direction ...
}
```

Executed 16 times/second

on lift thread

TestLiftGui.java

Lift GUI thread safety

- Dogma 1, no long-running on event thread:
  - **`sleep()`** happens on lift threads, not event thread
- Dogma 2, only event thread works on GUI:
  - Lift thread calls **`shaft.moveTo`**,
  - which calls **`repaint()`**,
  - so event thread later calls **`paint(g)`**, OK
- Lift and event threads access **`stops[]`** array
  - guarded by lock on lift instance **`this`**
- Only lift thread accesses **`floor`** and **`direction`**
  - not guarded by a lock

Lift modeling reflection

- Seems reasonable to have a thread per lift
  - because they move concurrently
- Why not a thread for the controller?
  - because activated only by the external buttons
  - but what about supervising the lifts, timeouts? E.g. if the lift sent to floor 4 going Up gets stuck at floor 3 by some fool blocking the open door?
- In Erlang, with message-passing, use
  - a "process" (task) for each lift
  - a "process" (task) for each floor, a "local controller"
  - no central controller

Armstrong et al: Concurrent Programming in Erlang (1993) 11.1

- Also Akka library, week 12-13

This week

- Reading this week
  - Goetz et al chapter 9, 10.1, 10.2
  - McKenney: *Memory barriers,* chapters 1-4
- Exercises
  - You can write responsive and correct user interfaces involving concurrency
- Read before next week's lecture
  - Goetz chapter 12
  - Herlihy and Shavit chapter 3