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

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"

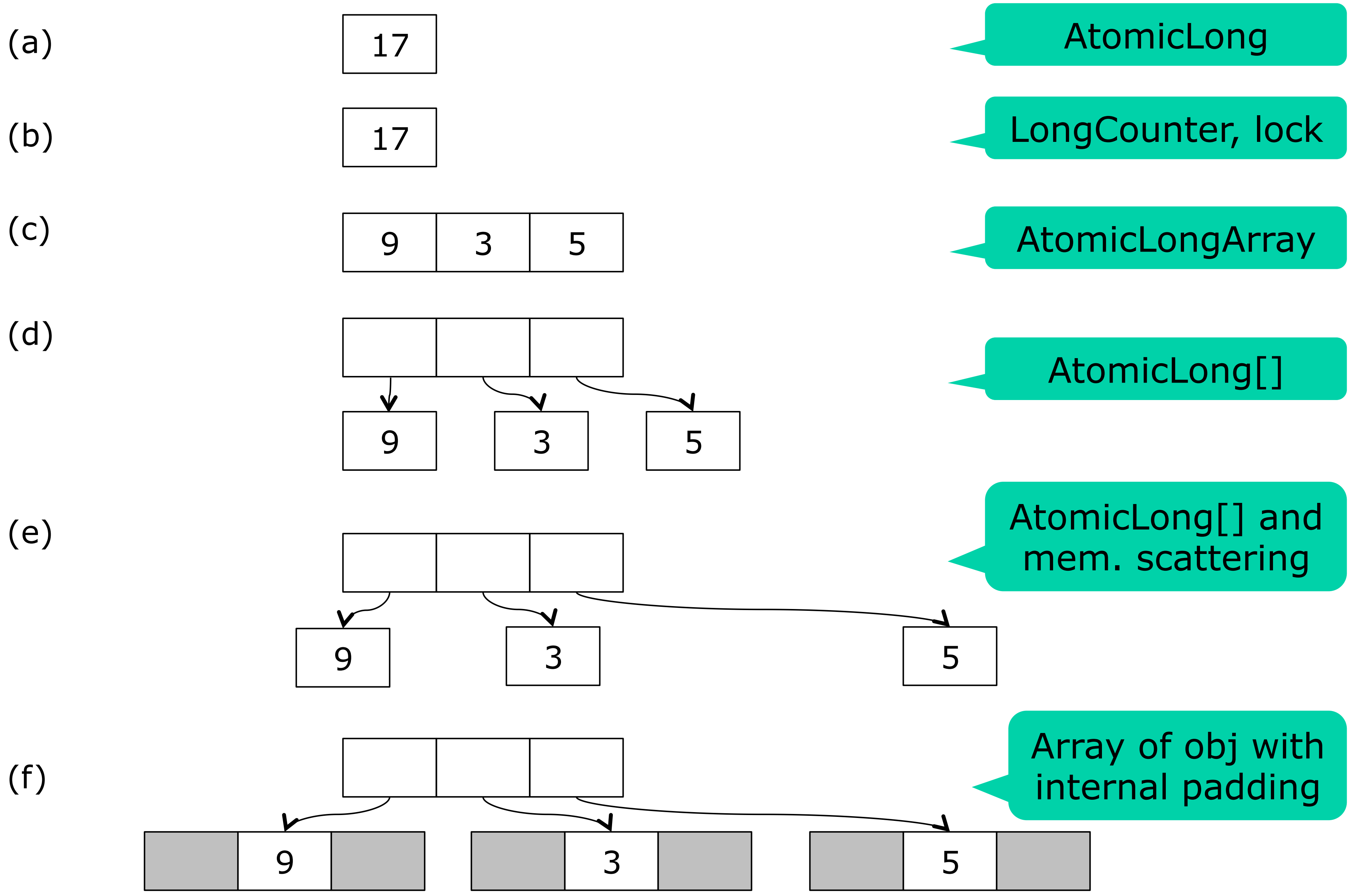
```
class NewLongAdder {
  private final static int NSTRIPES = 31;
  private final AtomicLong[] counters;
  ...
  public void add(long delta) {
    counters[Thread.currentThread().hashCode() % NSTRIPES].addAndGet(delta);
  }

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

Thread's hashcode selects stripe

TestLongAdders.java

- 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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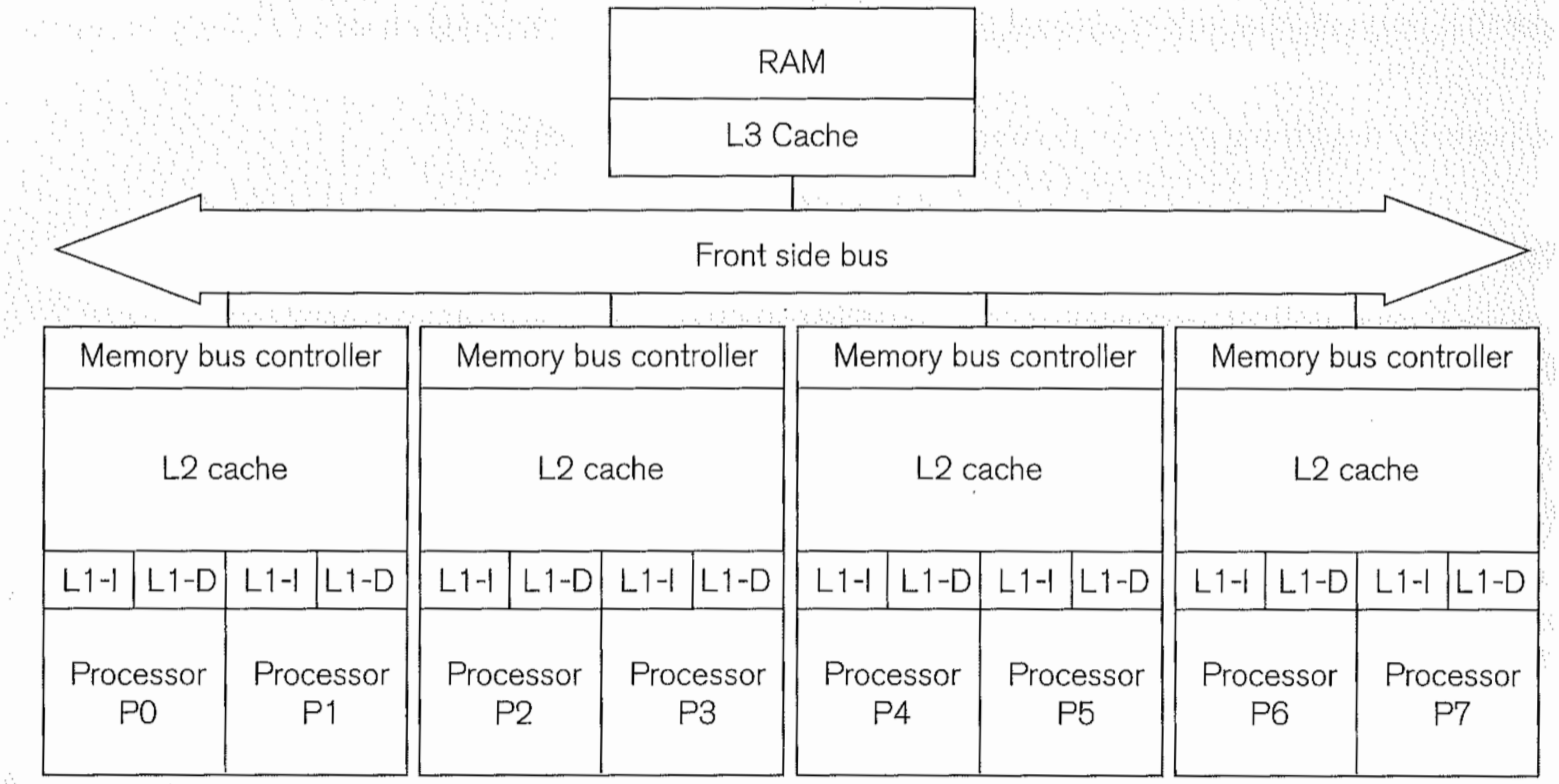
A typical multicore CPU with three levels of cache

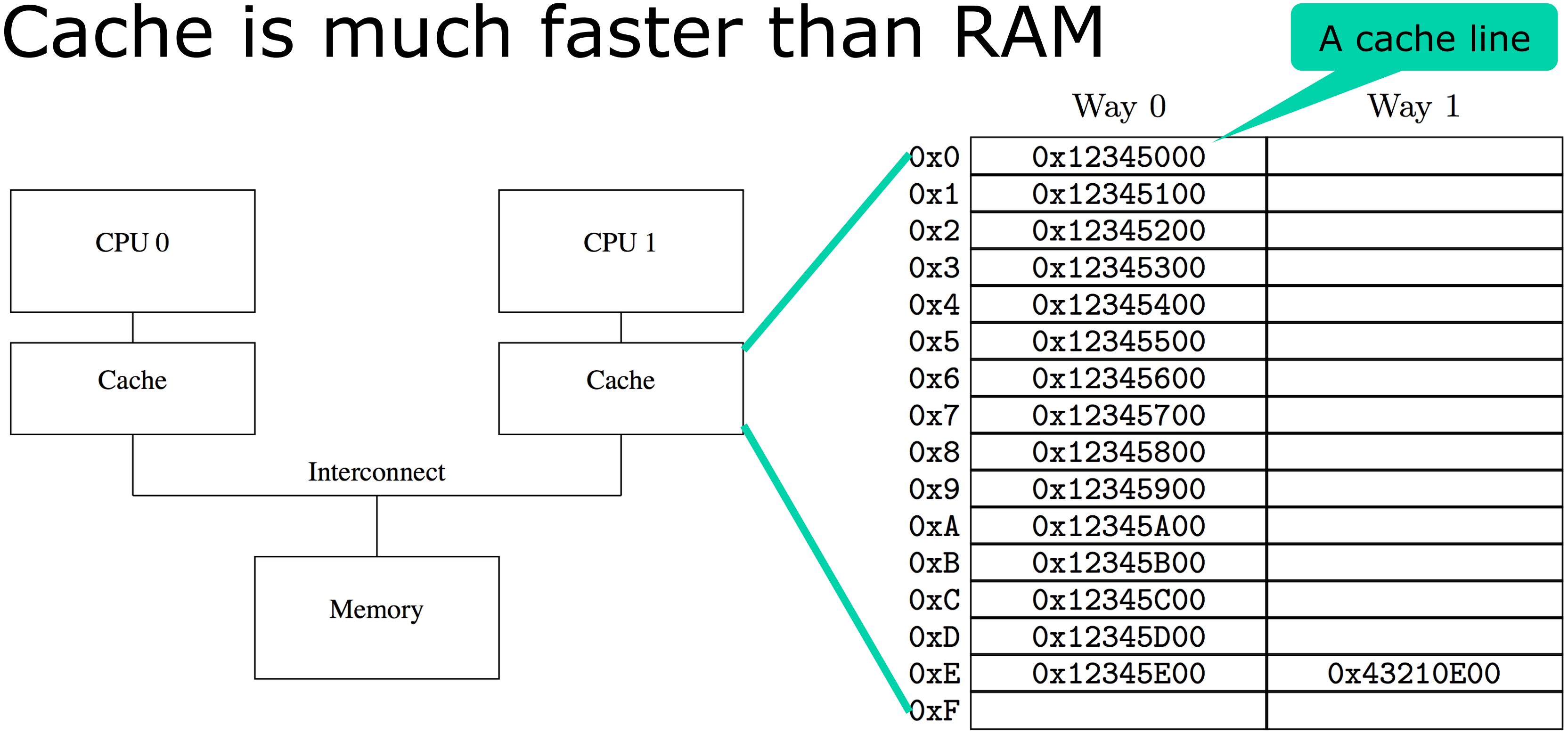


Lin & Snyder 2009, p. 16

- 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



McKenney 2010: Memory barriers

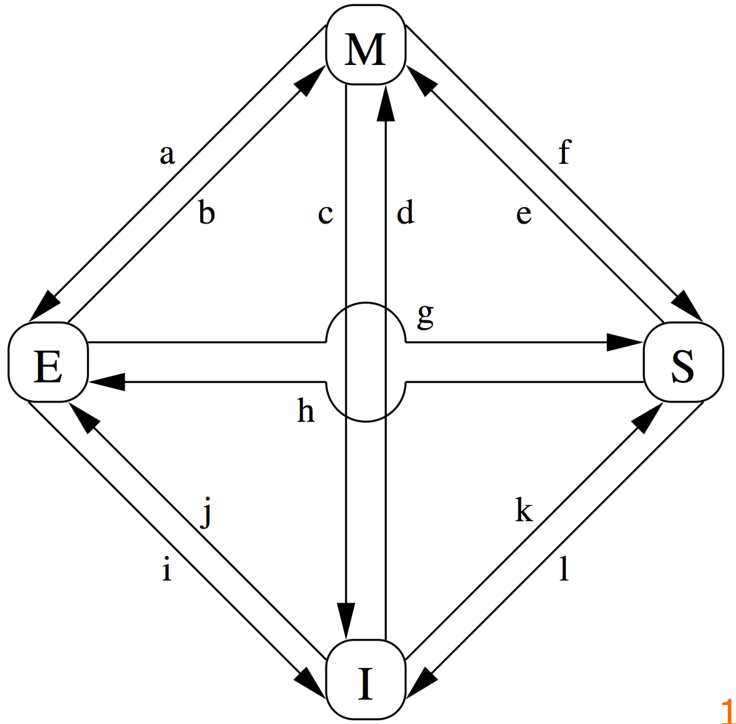
- Two caches may have different values for a given memory address

Fix 2: Get all caches to agree

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

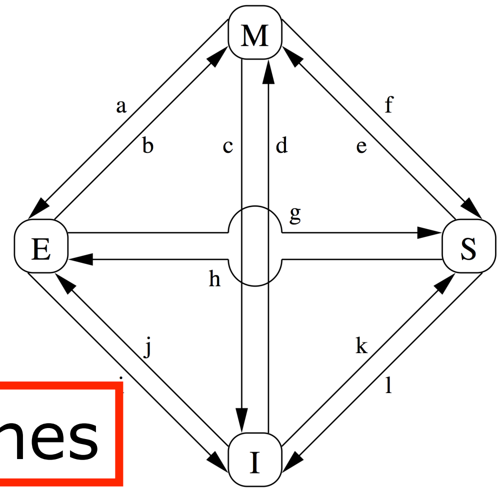
State	Cache line	Excl	RAM	To read	To write
Modified	Modified by me	Y	stale	from cache	to cache
Exclusive	Not modified	Y	fresh	from cache	to cache -> M
Shared	Others have it too	N	fresh	from cache	send invalidate
Invalid	Not in use by me	-	-	elsewhere	send invalidate

- 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 (rows M M Read, M M Write, E E Read, E M Write)

Shared immutable (rows S S Read, I S Read)

Shared mutable (rows S M Write, I M Write)

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

TestLongAdders.java

```
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();
    }
  }
}
```

Avoid side-by-side AtomicLong allocation

Unless JVM is too clever

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

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
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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

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

javax.swing.SwingWorker documentation

- 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

A short computation on the event thread

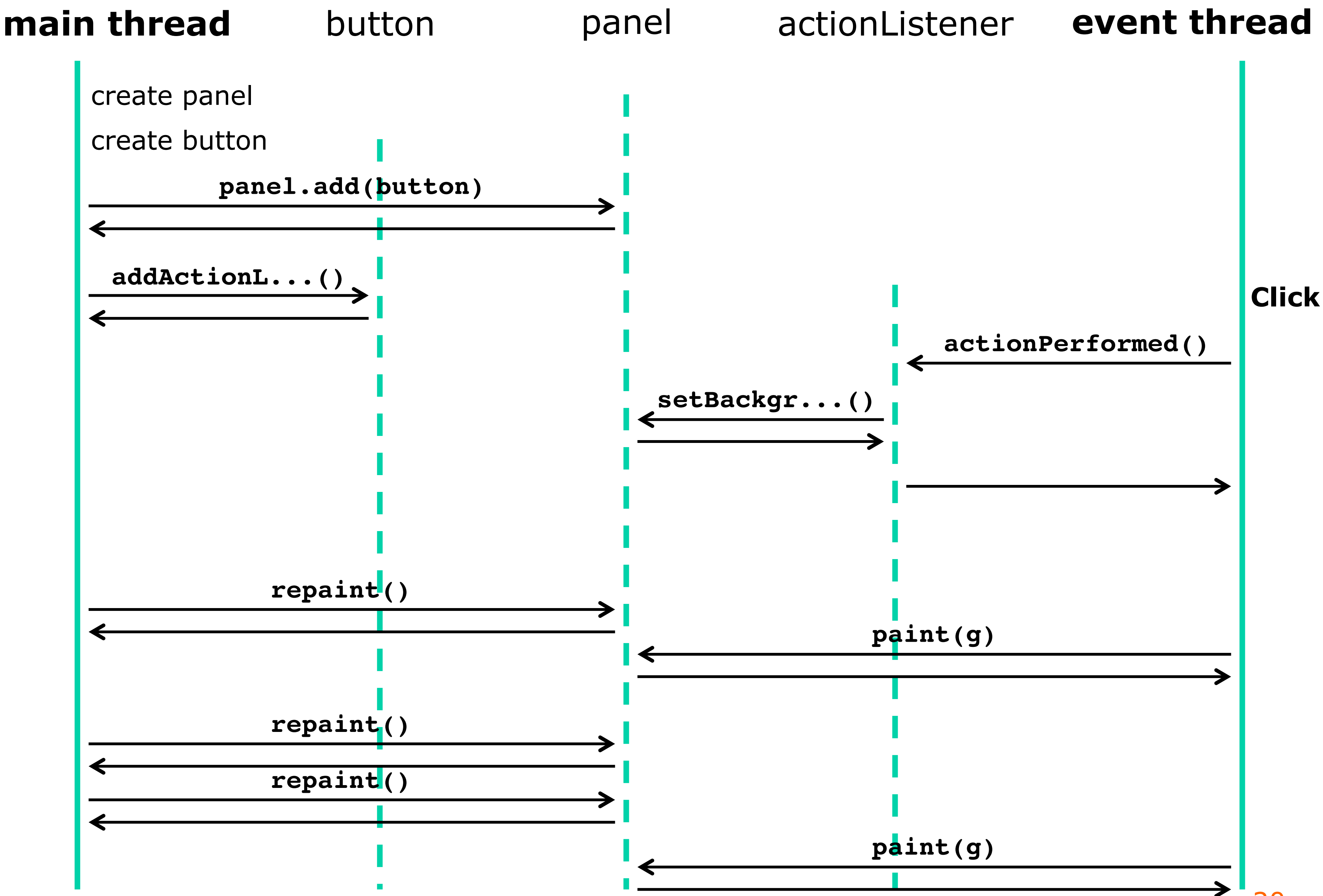
B 1

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

```
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

W 1

TestFecthWebGui.java

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

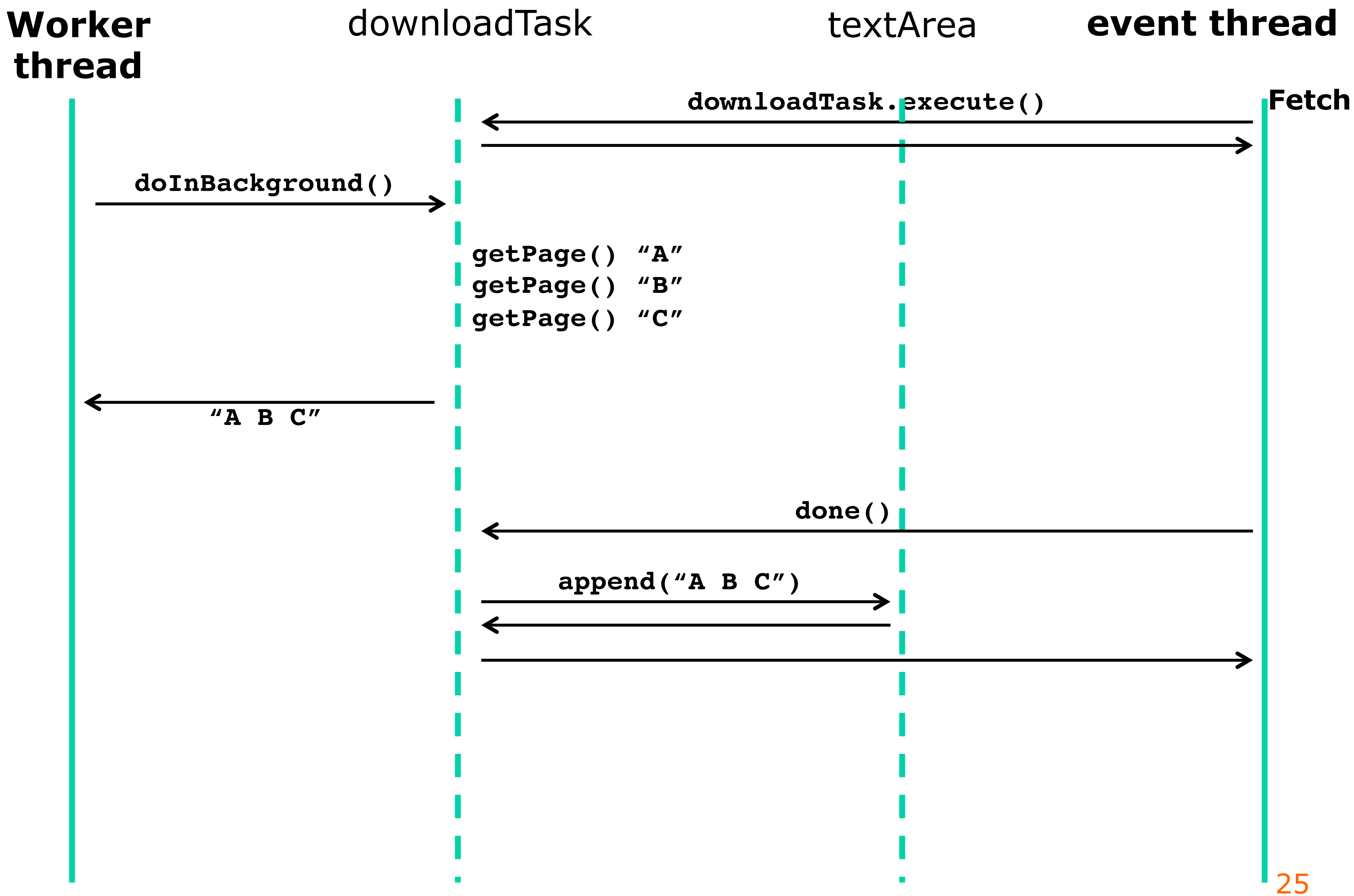
- Event thread runs **`execute()`**
- Worker thread runs **`doInBackground()`**
  - which returns the full result when computed
- Event thread runs **`done()`**
  - obtains the already-computed result with **`get()`**
  - and writes the result to the textArea

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"); }
} }
```

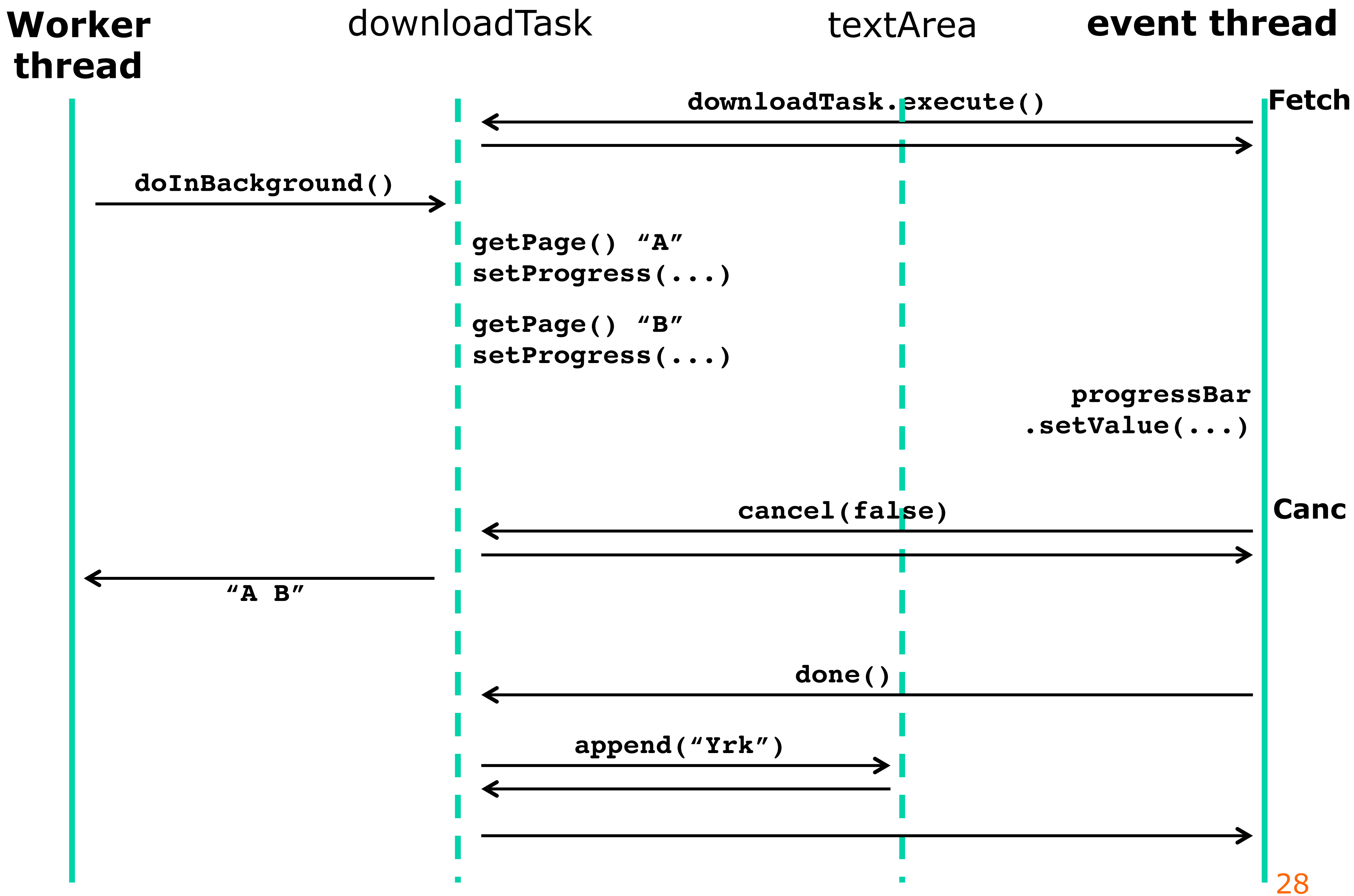
On worker thread

- In the GUI setup, add:

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

On event thread

Progress and cancellation



Show results gradually

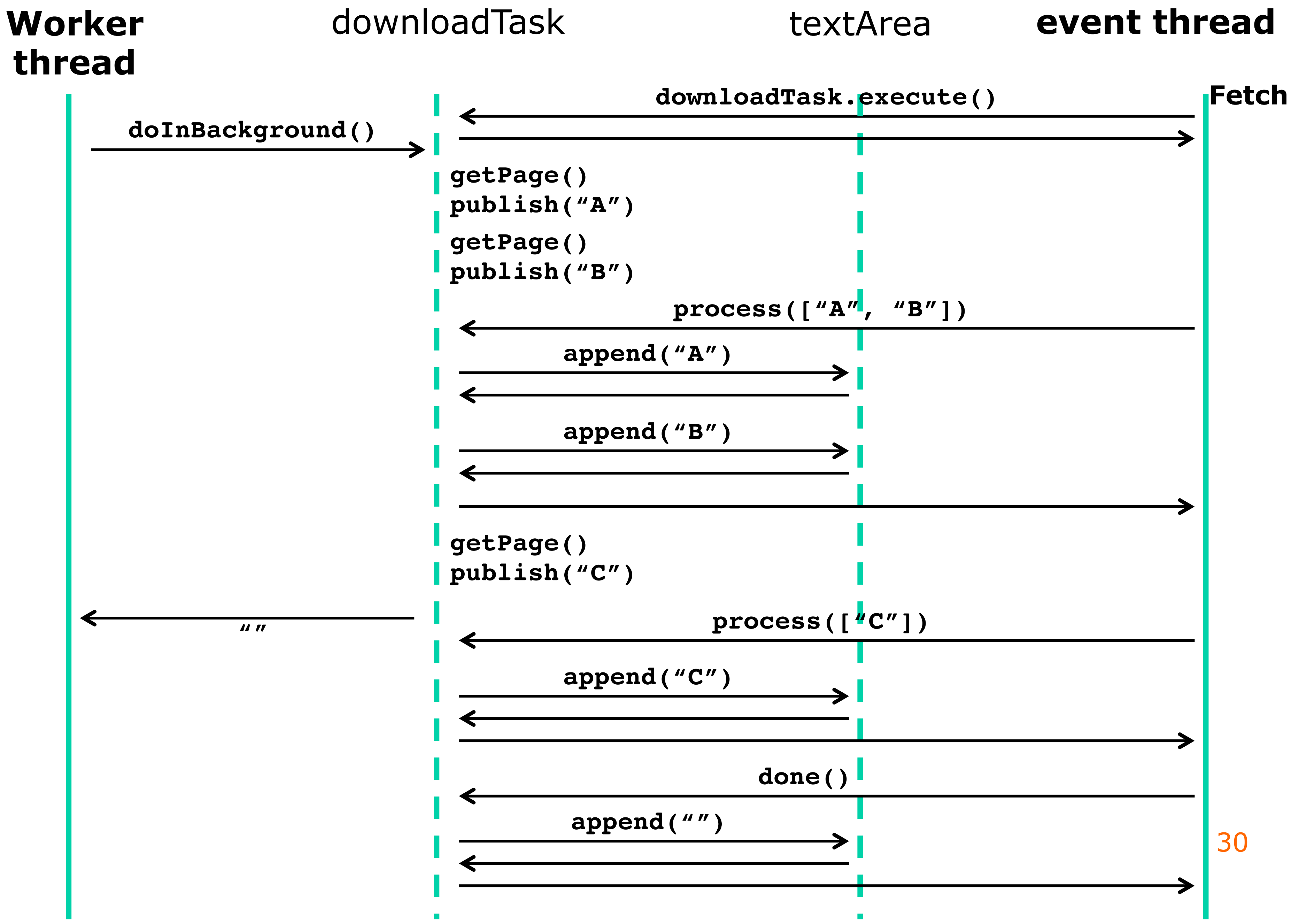
```
static class DownloadWorker extends SwingWorker<String,String> {
  public String doInBackground() {
    for (String url : urls) {
      String page = getPage(url, 200),
        result = String.format("%-40s%7d%n", url, page.length());
      publish(result);
    }
  }

  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

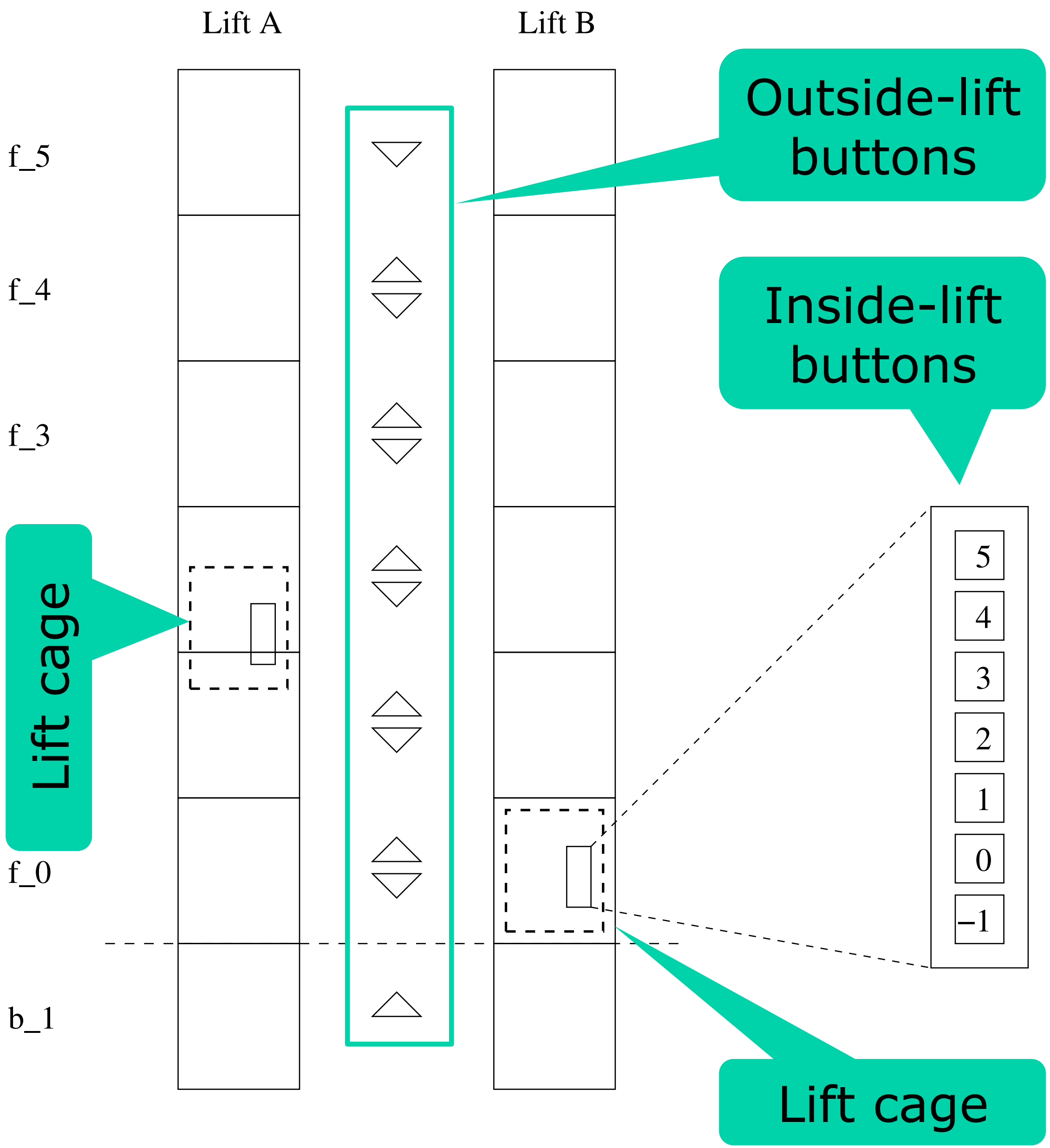
GUI gets built on the Event Thread

- 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



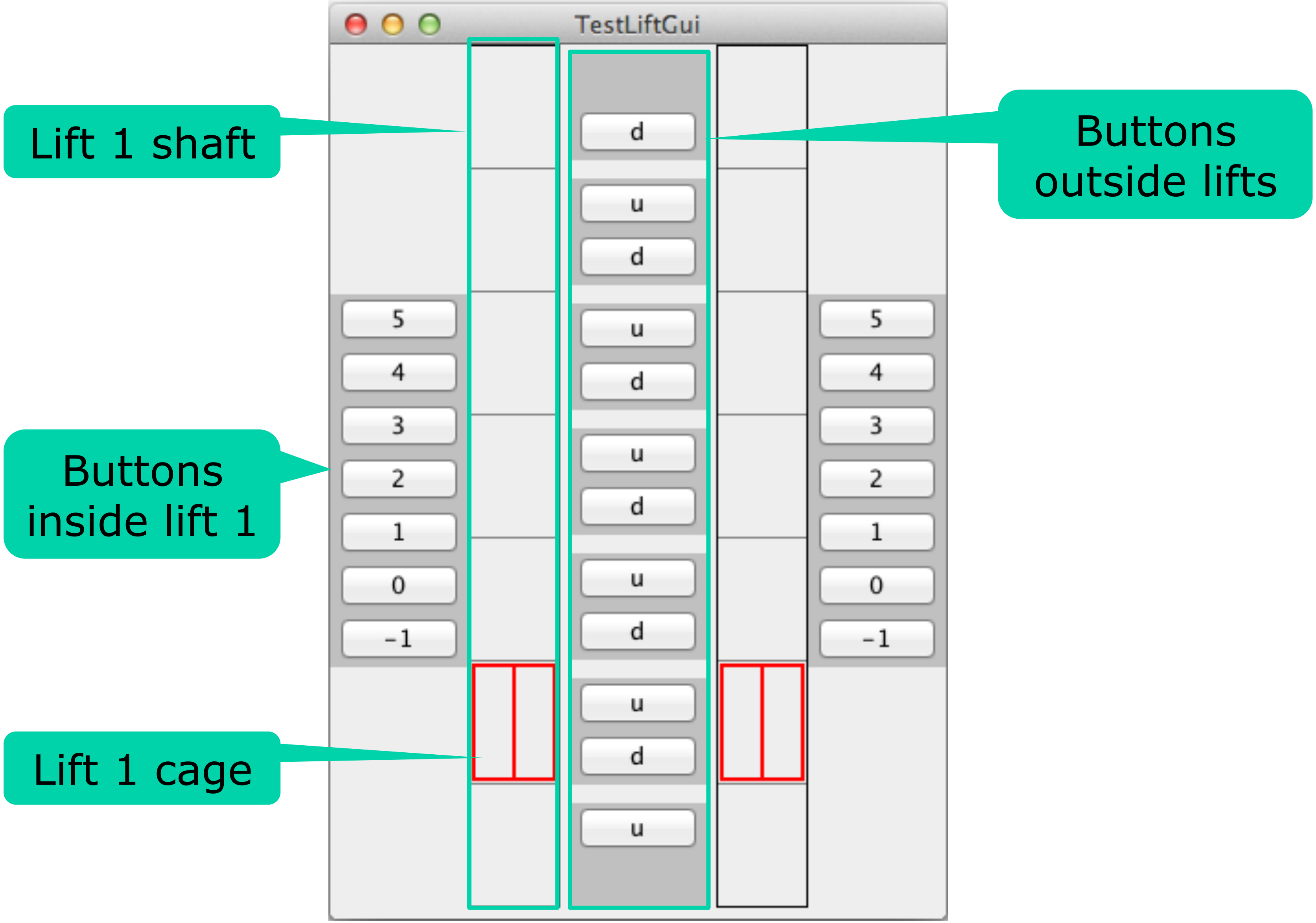
Concurrency:
2 lift cages move
26 buttons pressed

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
  - 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