Lecture #37

Today: Side excursions into nitty-gritty stuff: Threads, storage management.

Threads

- So far, all our programs consist of single sequence of instructions.
- Each such sequence is called a *thread* (for "thread of control") in Java.
- Java supports programs containing *multiple* threads, which (conceptually) run concurrently.
- Actually, on a uniprocessor, only one thread at a time actually runs, while others wait, but this is largely invisible.
- To allow program access to threads, Java provides the type `Thread` in `java.lang`. Each `Thread` contains information about, and controls, one thread.
- Simultaneous access to data from two threads can cause chaos, so are also constructs for controlled communication, allowing threads to *lock* objects, to *wait* to be notified of events, and to *interrupt* other threads.

But Why?

- Typical Java programs always have > 1 thread: besides the main program, others clean up garbage objects, receive signals, update the display, other stuff.
- When programs deal with asynchronous events, is sometimes convenient to organize into subprograms, one for each independent, related sequence of events.
- Threads allow us to insulate one such subprogram from another.
- GUIs often organized like this: application is doing some computation or I/O, another thread waits for mouse clicks (like 'Stop'), another pays attention to updating the screen as needed.
- Large servers like search engines may be organized this way, with one thread per request.
- And, of course, sometimes we *do* have a real multiprocessor.

Java Mechanics

- To specify the actions "walking" and "chewing gum":

```
class Chewer1 implements Runnable {
   public void run()
     { while (true) ChewGum(); }
}
class Walker1 implements Runnable {
   public void run()
     { while (true) Walk(); }
}
```

```
// Walk and chew gum
Thread chomp
  = new Thread(new
Chewer1());
Thread clomp
  = new Thread(new
Walker1());
chomp.start(); clomp.start();
```

- Concise Alternative (uses fact that Thread implements Runnable):

```
class Chewer2 extends Thread {
  public void run()
    { while (true) ChewGum(); }
}
class Walker2 extends Thread {
  public void run()
    { while (true) Walk(); }
}
```

```
Thread chomp = new Chewer2(),
       clomp = new Walker2();
chomp.start();
clomp.start();
```

Avoiding Interference

- When one thread has data for another, one must wait for the other to be ready.
- Likewise, if two threads use the same data structure, generally only one should modify it at a time; other must wait.
- E.g., what would happen if two threads simultaneously inserted an item into a linked list at the same point in the list?
- A: Both could conceivably execute

```
p.next = new ListCell(x, p.next);
```

  with the *same* values of `p` and `p.next`; one insertion is lost.
- Can arrange for only one thread at a time to execute a method on a particular object with either of the following equivalent definitions:

```
void f(...) {
  synchronized (this) {
    body of f
  }
}
```

```
synchronized void f(...) {
  body of f
}
```

Communicating the Hard Way

- Communicating data is tricky: the faster party must wait for the slower.
- Obvious approaches for sending data from thread to thread don't work:

```
class DataExchanger {
   Object value = null;
   Object receive() {
      Object r; r = null;
      while (r == null)
        { r = value; }
      value = null;
      return r;
   }
   void deposit(Object data) {
      while (value != null) { }
      value = data;
   }
}
```

```
DataExchanger exchanger
  = new DataExchanger();

--------------------------------

// thread1 sends to thread2 with
exchanger.deposit("Hello!");

--------------------------------

// thread2 receives from thread1 with
msg = (String) exchanger.receive();
```

- BAD: One thread can monopolize machine while waiting; two threads executing `deposit` or `receive` simultaneously cause chaos.

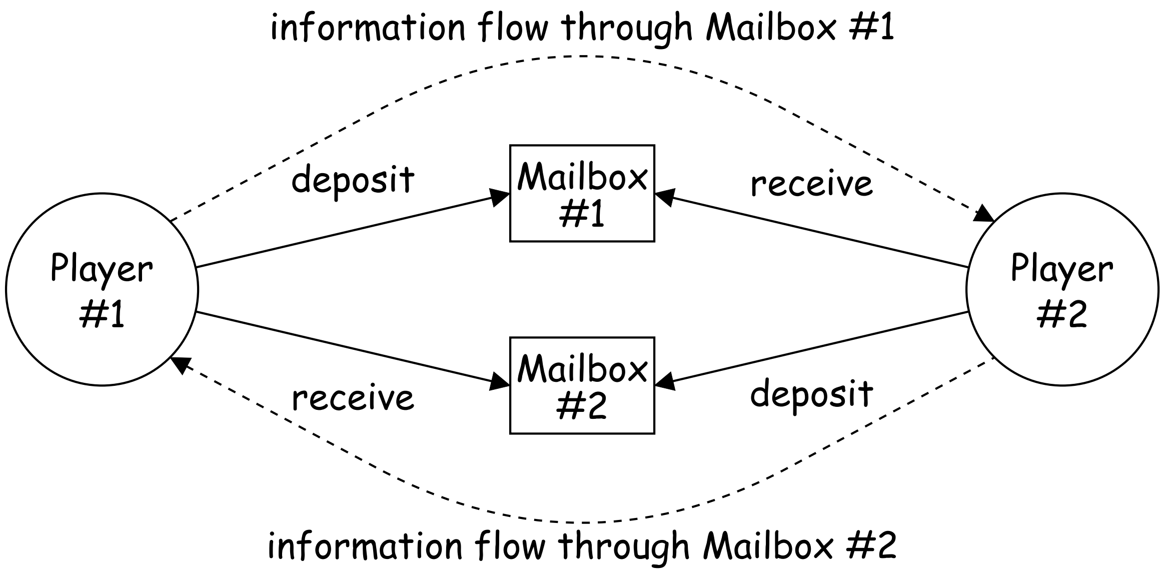
Primitive Java Facilities

- `wait` method on Object makes thread wait (not using processor) until notified by `notifyAll`, unlocking the Object while it waits.
- Example, `ucb.util.mailbox` has something like this (simplified):

```
interface Mailbox {
  void deposit(Object msg) throws InterruptedException;
  Object receive() throws InterruptedException;
}

class QueuedMailbox implements Mailbox {
  private List<Object> queue = new LinkedList<Object>();

  public synchronized void deposit(Object msg) {
    queue.add(msg);
    this.notifyAll(); // Wake any waiting receivers
  }

  public synchronized Object receive() throws InterruptedException {
    while (queue.isEmpty()) wait();
    return queue.remove(0);
  }
}
```

Message-Passing Style

- Use of Java primitives very error-prone. Wait until CS162.
- Mailboxes are higher-level, and allow the following program structure:



- Where each Player is a thread that looks like this:

```
while (! gameOver()) {
  if (myMove())
    outBox.deposit(computeMyMove(lastMove));
  else
    lastMove = inBox.receive();
}
```

More Concurrency

- Previous example can be done other ways, but mechanism is very flexible.
- E.g., suppose you want to think during opponent's move:

```
while (!gameOver()) {
  if (myMove())
    outBox.deposit(computeMyMove(lastMove));
  else {
    do {
      thinkAheadALittle();
      lastMove = inBox.receiveIfPossible();
    } while (lastMove == null);
}
```

- `receiveIfPossible` (written `receive(0)` in our actual package) doesn't wait; returns `null` if no message yet, perhaps like this:

```
public synchronized Object receiveIfPossible()
    throws InterruptedException {
  if (queue.isEmpty())
    return null;
  return queue.remove(0);
}
```

Coroutines

- A *coroutine* is a kind of synchronous thread that explicitly hands off control to other coroutines so that only one executes at a time, like Python generators. Can get similar effect with threads and mailboxes.
- Example: recursive inorder tree iterator:

```
class TreeIterator extends Thread {
  Tree root; Mailbox r;
  TreeIterator(Tree T, Mailbox r) {
    this.root = T; this.dest = r;
  }
  public void run() {
    traverse(root);
    r.deposit(End marker);
  }
  void traverse(Tree t) {
    if (t == null) return;
    traverse(t.left);
    r.deposit(t.label);
    traverse(t.right);
  }
}
```

```
void treeProcessor(Tree T) {
  Mailbox m = new QueuedMailbox();
  new TreeIterator(T, m).start();
  while (true) {
     Object x = m.receive();
     if (x is end marker)
        break;
     do something with x;
  }
}
```

Use In GUIs

- Jave runtime library uses a special thread that does nothing but wait for *events* like mouse clicks, pressed keys, mouse movement, etc.
- You can designate an object of your choice as a *listener;* which means that Java's event thread calls a method of that object whenever an event occurs.
- As a result, your program can do work while the GUI continues to respond to buttons, menus, etc.
- Another special thread does all the drawing. You don't have to be aware when this takes place; just ask that the thread wake up whenever you change something.

Highlights of a GUI Component

```
/** A widget that draws multi-colored lines indicated by mouse. */
class Lines extends JComponent implements MouseListener {
  private List<Point> lines = new ArrayList<Point>();

  Lines() {  // Main thread calls this to create one
    setPreferredSize(new Dimension(400, 400));
    addMouseListener(this);
  }
  public synchronized void paintComponent(Graphics g) { // Paint thread
    g.setColor(Color.white);   g.fillRect(0, 0, 400, 400);
    int x, y;   x = y = 200;
    Color c = Color.black;
    for (Point p : lines)
      g.setColor(c); c = chooseNextColor(c);
      g.drawLine(x, y, p.x, p.y); x = p.x; y = p.y;
    }
  }
  public synchronized void mouseClicked(MouseEvent e) // Event thread
    { lines.add(new Point(e.getX(), e.getY())); repaint(); }
  ...
}
```

Interrupts

- An *interrupt* is an event that disrupts the normal flow of control of a program.
- In many systems, interrupts can be totally *asynchronous*, occurring at arbitrary points in a program, the Java developers considered this unwise; arranged that interrupts would occur only at controlled points.
- In Java programs, one thread can interrupt another to inform it that something unusual needs attention:

```
otherThread.interrupt();
```

- But `otherThread` does not receive the interrupt until it waits: methods `wait`, `sleep` (wait for a period of time), `join` (wait for thread to terminate), and mailbox deposit and receive.
- Interrupt causes these methods to throw `InterruptedException`, so typical use is like this:

```
try {
  msg = inBox.receive();
} catch (InterruptedException e) { HandleEmergency(); }
```

Remote Mailboxes (A Side Excursion)

- RMI: Remote Method Interface allows one program to refer to objects in another program.
- We use it to allow mailboxes in one program be received from or deposited into in another.
- To use this, you define an *interface* to the remote object:

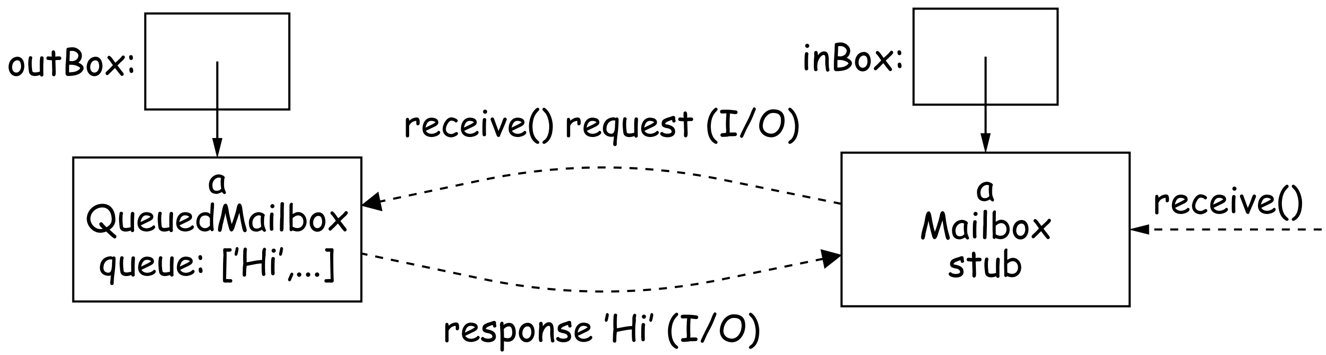
```
import java.rmi.*;
interface Mailbox extends Remote {
  void deposit(Object msg)
    throws InterruptedException, RemoteException;
  Object receive()
    throws InterruptedException, RemoteException;
  ...
}
```

- On machine that actually will contain the object, you define

```
class QueuedMailbox ... implements Mailbox {
    Same implementation as before, roughly
}
```

Remote Objects Under the Hood

```
// On machine #1:                // On Machine #2:
Mailbox outBox                    Mailbox inBox
  = new QueuedMailbox();          = get outBox from machine #1
```



- Because `Mailbox` is an interface, hides fact that on Machine #2 doesn't actually have direct access to it.
- Requests for method calls are relayed by I/O to machine that has real object.
- Any argument or return type OK if it also implements `Remote` or can be *serialized*—turned into stream of bytes and back, as can primitive types and String.
- Because I/O involved, expect failures, hence every method can throw RemoteException (subtype of IOException).

Scope and Lifetime

- *Scope* of a declaration is portion of program text to which it applies (is *visible*).
  - Need not be contiguous.
  - In Java, is static: independent of data.
- *Lifetime* or *extent* of storage is portion of program execution during which it exists.
  - Always contiguous
  - Generally dynamic: depends on data
- Classes of extent:
  - *Static:* entire duration of program
  - *Local* or *automatic:* duration of call or block execution (local variable)
  - *Dynamic:* From time of allocation statement (**new**) to deallocation, if any.

Explicit vs. Automatic Freeing

- Java has no explicit means to free dynamic storage.
- However, when no expression in any thread can possibly be influenced by or change an object, it might as well not exist:

```
IntList wasteful()
{
  IntList c = new IntList(3, new IntList(4, null));
  return c.tail;
  // variable c now deallocated, so no way
  // to get to first cell of list
}
```

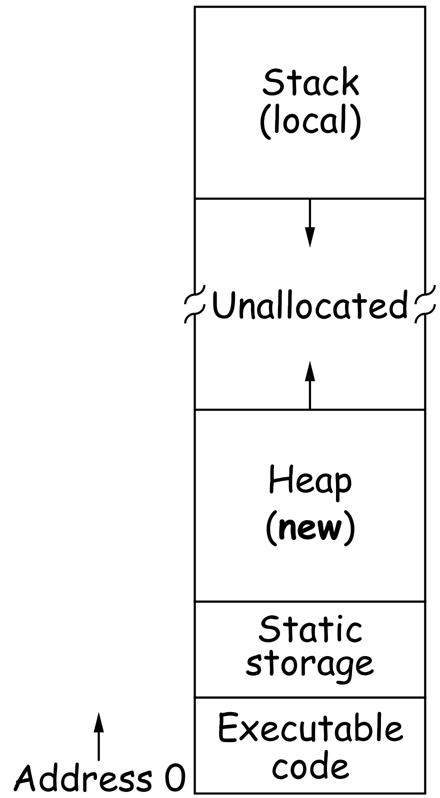
- At this point, Java runtime, like Scheme's, recycles the object `c` pointed to: *garbage collection*.

Under the Hood: Allocation

- Java pointers (references) are represented as integer addresses.
- Corresponds to machine's own practice.
- In Java, cannot convert integers $\leftrightarrow$ pointers,
- But crucial parts of Java runtime implemented in C, or sometimes machine code, where you can.
- Crude allocator in C:

```
char store[STORAGE_SIZE];  // Allocated array
size_t remainder = STORAGE_SIZE;

/** A pointer to a block of at least N bytes of storage */
void* simpleAlloc(size_t n) { // void*: pointer to anything
  if (n > remainder) ERROR();
  remainder = (remainder - n) & ~0x7;  // Make multiple of 8
  return (void*) (store + remainder);
}
```

Example of Storage Layout: Unix



- OS gives way to turn chunks of unallocated region into heap.
- Happens automatically for stack.

Explicit Deallocating

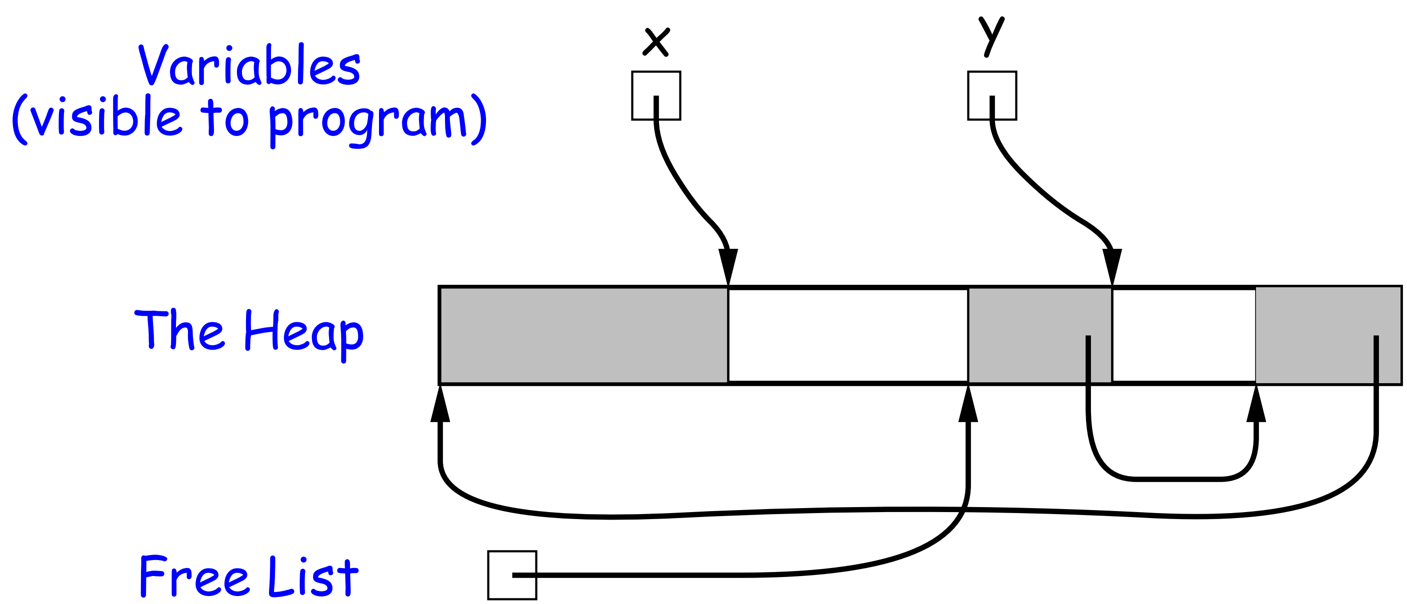
- C/C++ normally require explicit deallocation, because of
  - Lack of run-time information about what is array
  - Possibility of converting pointers to integers.
  - Lack of run-time information about *unions:*

```
union Various {
  int Int;
  char* Pntr;
  double Double;
} X;  // X is either an int, char*, or double
```

- Java avoids all three problems; automatic collection possible.
- Explicit freeing can be somewhat faster, but rather error-prone:
  - Memory corruption
  - Memory leaks

Free Lists

- Explicit allocator grabs chunks of storage from OS and gives to applications.
- Or gives recycled storage, when available.
- When storage is freed, added to a *free list* data structure to be recycled.
- Used both for explicit freeing and some kinds of automatic garbage collection.

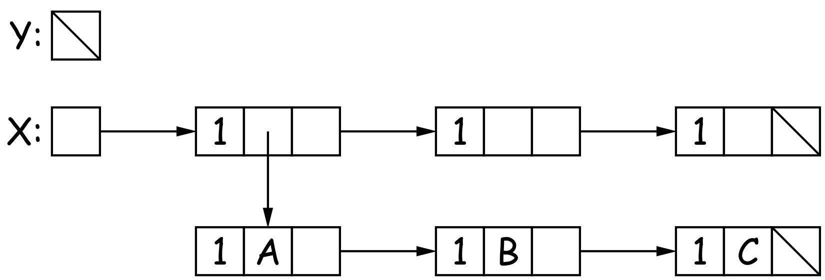


Free List Strategies

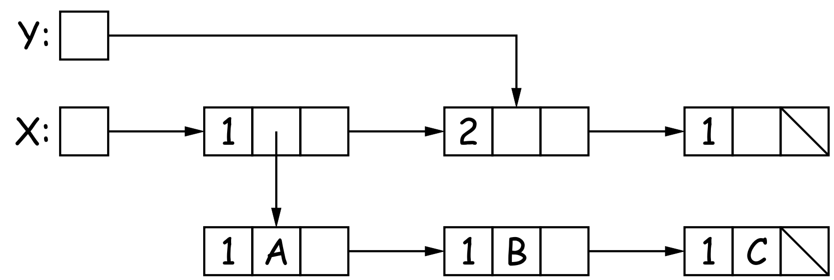
- Memory requests generally come in multiple sizes.
- Not all chunks on the free list are big enough, and one may have to search for a chunk and break it up if too big.
- Various strategies to find a chunk that fits have been used:
  - *Sequential fits:*
    - Link blocks in LIFO or FIFO order, or sorted by address.
    - Coalesce adjacent blocks.
    - Search for *first fit* on list, *best fit* on list, or *next fit* on list after last-chosen chunk.
  - *Segregated fits:* separate free lists for different chunk sizes.
  - *Buddy systems:* A kind of segregated fit where some newly adjacent free blocks of one size are easily detected and combined into bigger chunks.
- Coalescing blocks reduces *fragmentation* of memory into lots of little scattered chunks.

Garbage Collection: Reference Counting

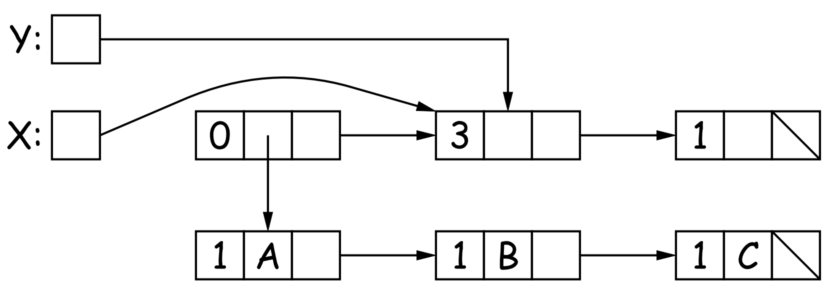
- Idea: Keep count of number of pointers to each object. Release when count goes to 0.

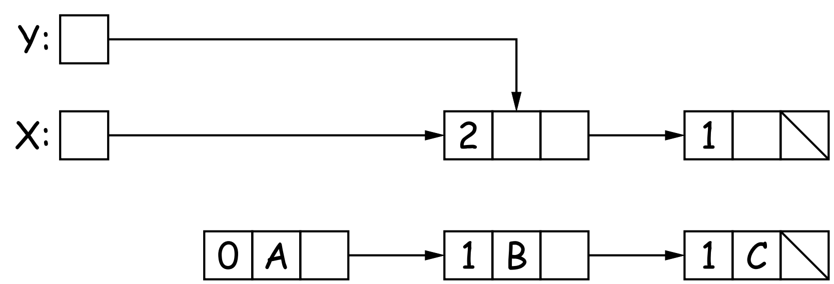


`Y = X.tail;`

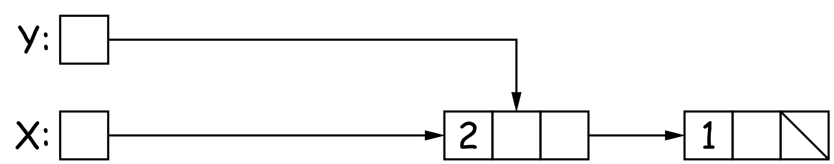


`X = Y;`



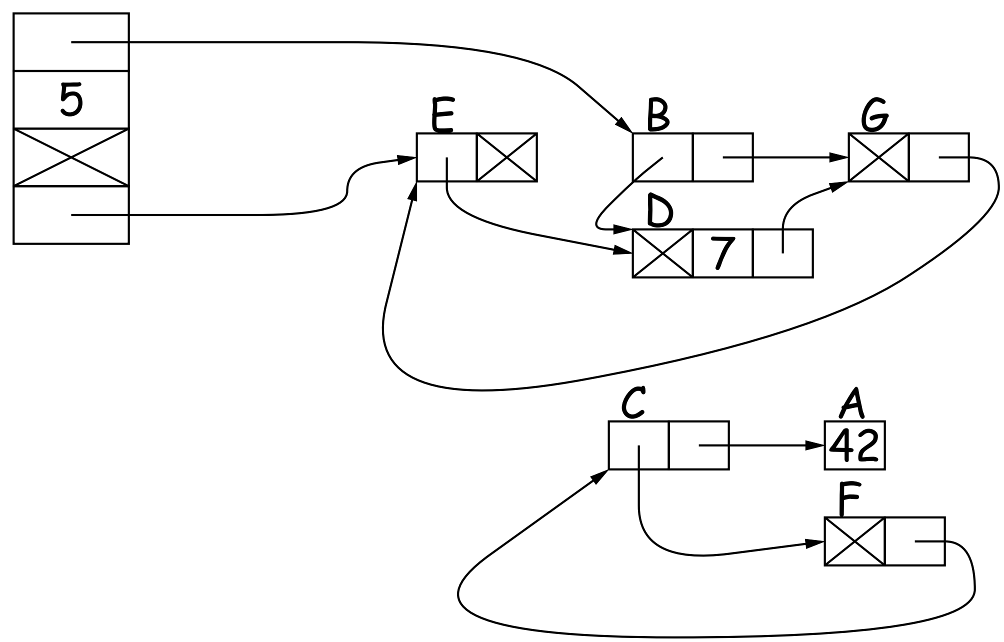


. . . etc., until:

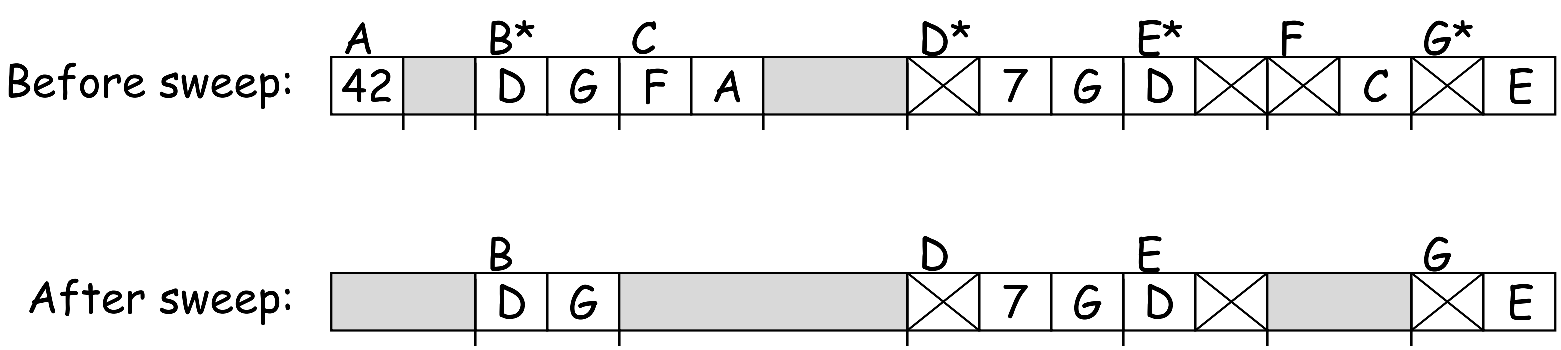


Garbage Collection: Mark and Sweep

Roots (locals + statics)



1. Traverse and mark graph of objects.
2. Sweep through memory, freeing unmarked objects.



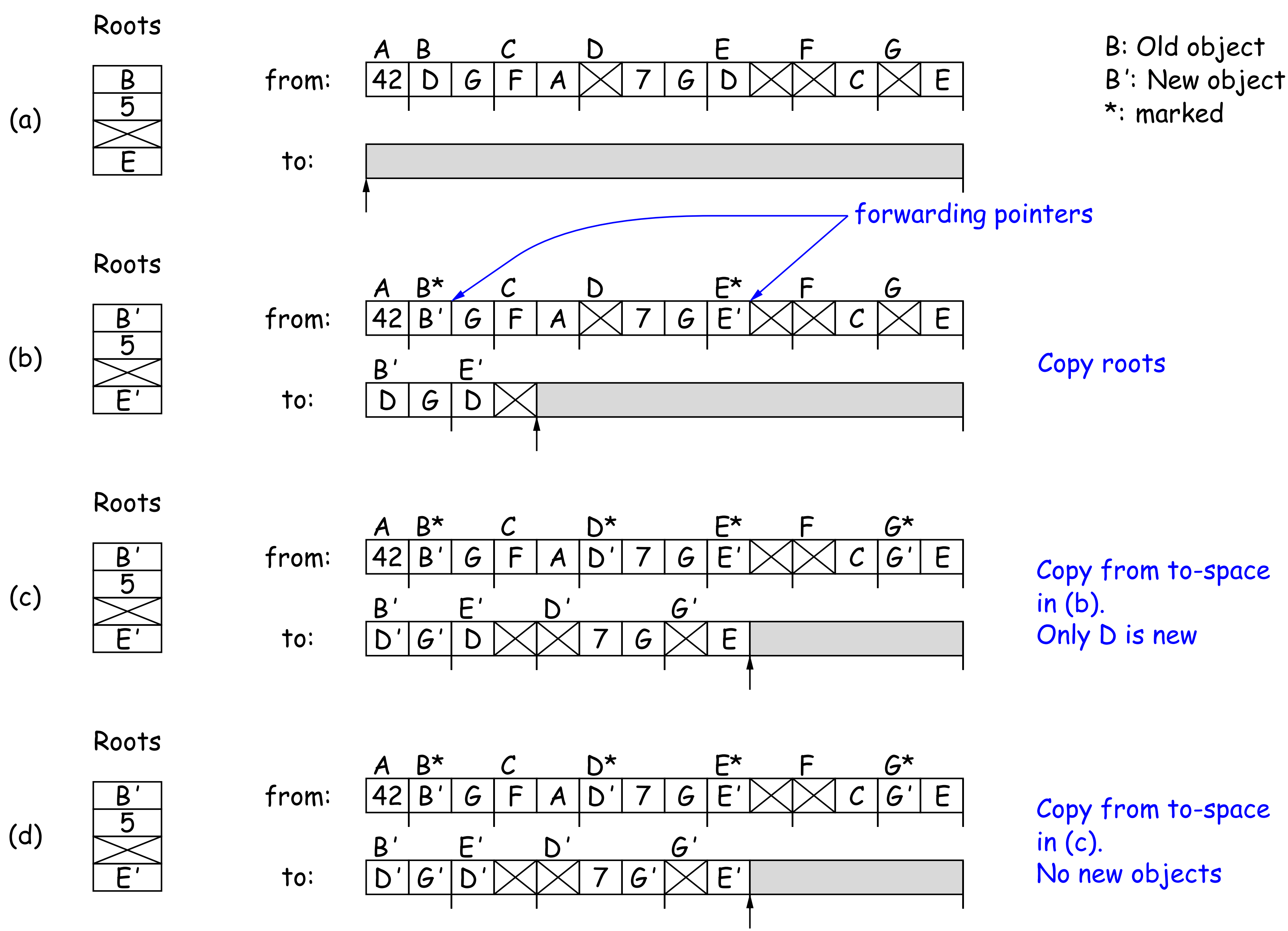
Cost of Mark-and-Sweep

- Mark-and-sweep algorithms don't move any exisiting objects—pointers stay the same.
- The total amount of work depends on the amount of memory swept—i.e., the total amount of active (non-garbage) storage + amount of garbage. Not necessarily a big hit: the garbage had to be active at one time, and hence there was always some "good" processing in the past for each byte of garbage scanned.

Copying Garbage Collection

- Another approach: *copying garbage collection* takes time proportional to amount of active storage:
  - Traverse the graph of active objects breadth first, *copying* them into a large contiguous area (called "to-space").
  - As you copy each object, mark it and put a *forwarding pointer* into it that points to where you copied it.
  - The next time you have to copy an already marked object, just use its forwarding pointer instead.
  - When done, the space you copied from ("from-space") becomes the next to-space; in effect, all its objects are freed in constant time.

Copying Garbage Collection Illustrated



Most Objects Die Young: Generational Collection

- Most older objects stay active, and need not be collected.
- Would be nice to avoid copying them over and over.
- *Generational garbage collection* schemes have two (or more) from spaces: one for newly created objects (*new space*) and one for "tenured" objects that have survived garbage collection (*old space*).
- A typical garbage collection collects only in new space, ignores pointers from new to old space, and moves objects to old space.
- As roots, uses usual roots plus pointers in old space that have changed (so that they might be pointing to new space).
- When old space full, collect all spaces.
- This approach leads to much smaller *pause times* in interactive systems.

There's Much More

- These are just highlights.
- Lots of work on how to implement these ideas efficiently.
- *Distributed garbage collection:* What if objects scattered over many machines?
- *Real-time collection:* where predictable pause times are important, leads to *incremental* collection, doing a little at a time.