Programs as Data
Real-world abstract machines for Java and C#/.NET.
Garbage collection techniques

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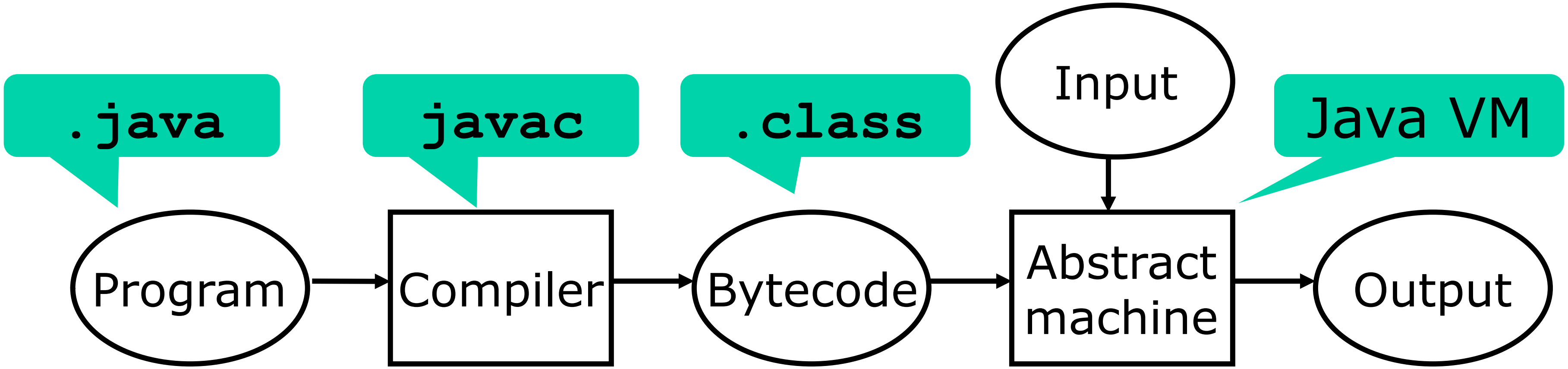
Today

- Java Virtual Machine
- .NET Common Language Infrastructure (CLI)
- Garbage collection (GC) techniques
  - Reference-counting
  - Mark-sweep
  - Two-space stop and copy
  - The garbage collectors in JVM and .NET
- List-C, a version of Micro-C with a heap and GC



Example Java program (ex6java.java)

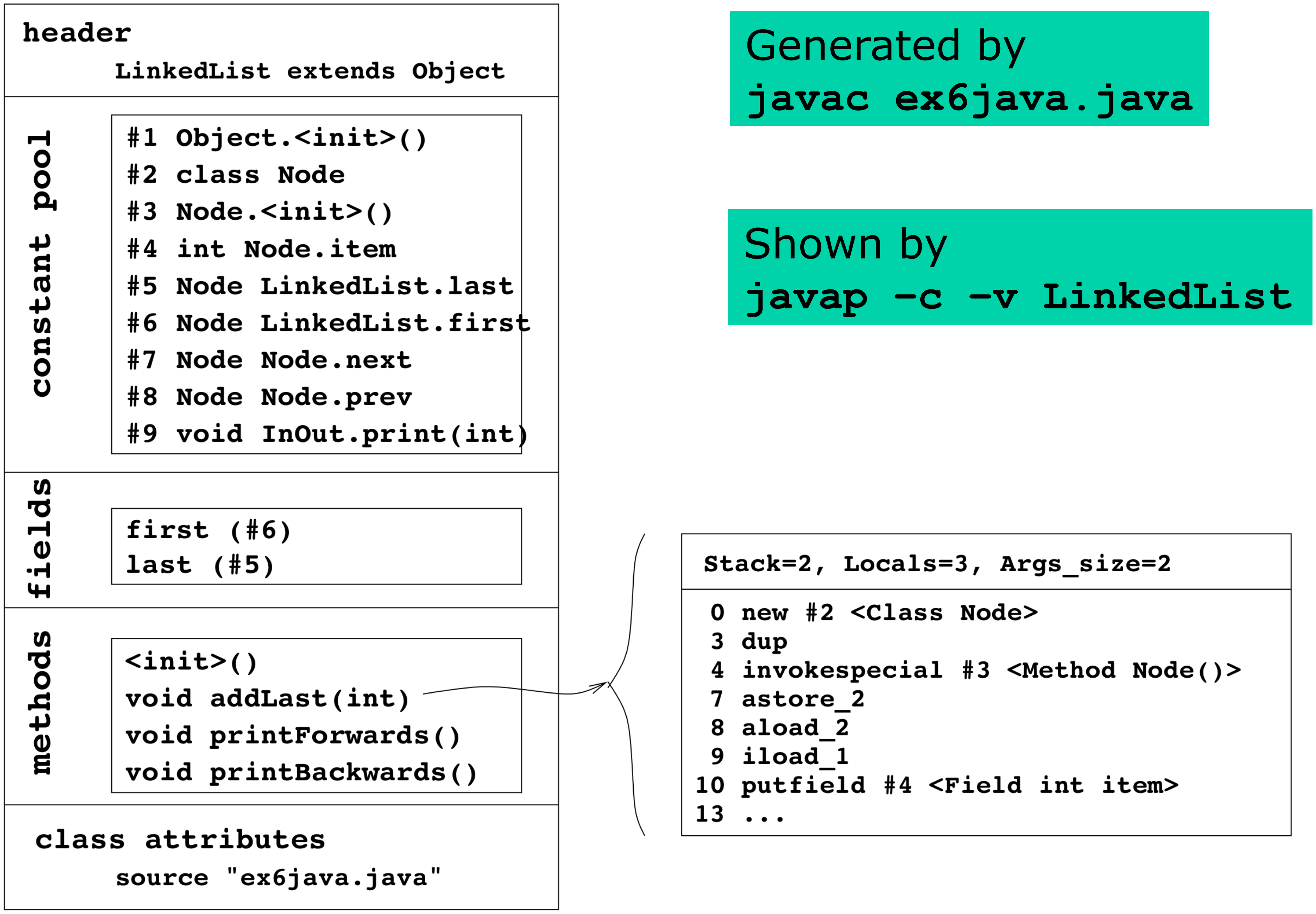
```
class Node extends Object {
  Node next;
  Node prev;
  int item;
}
```

```
class LinkedList extends Object {
  Node first, last;

  void addLast(int item) {
    Node node = new Node();
    node.item = item;
    if (this.last == null) {
      this.first = node;
      this.last = node;
    } else {
      this.last.next = node;
      node.prev = this.last;
      this.last = node;
    }
  }

  void printForwards() { ... }
  void printBackwards() { ... }
}
```

JVM class file (LinkedList.class)

Generated by
`javac ex6java.java`

Shown by
`javap -c -v LinkedList`



header

```
LinkedList extends Object
```

constant pool

```
#1 Object.<init>()
#2 class Node
#3 Node.<init>()
#4 int Node.item
#5 Node LinkedList.last
#6 Node LinkedList.first
#7 Node Node.next
#8 Node Node.prev
#9 void InOut.print(int)
```

fields

```
first (#6)
last (#5)
```

methods

```
<init>()
void addLast(int)
void printForwards()
void printBackwards()
```

class attributes

```
source "ex6java.java"
```

```
Stack=2, Locals=3, Args_size=2

 0 new #2 <Class Node>
 3 dup
 4 invokespecial #3 <Method Node()>
 7 astore_2
 8 aload_2
 9 iload_1
10 putfield #4 <Field int item>
13 ...
```

Some JVM bytecode instructions

Kind	Example instructions
push constant	iconst, ldc, aconst_null, …
arithmetic	iadd, isub, imul, idiv, irem, ineg, iinc, fadd, …
load local variable	iload, aload, fload, …
store local variable	istore, astore, fstore, …
load array element	iaload, baload, aaload, …
stack manipulation	swap, pop, dup, dup_x1, dup_x2, …
load field	getfield, getstatic
method call	invokestatic, invokevirtual, invokespecial
method return	return, ireturn, areturn, freturn, …
unconditional jump	goto
conditional jump	ifeq, ifne, iflt, ifle, …; if_icmpeq, if_icmpne, …
object-related	new, instanceof, checkcast

Type prefixes: i=int, a=object, f=float, d=double, s=short, b=byte, …

JVM bytecode verification

The JVM bytecode is *verified at loadtime,* before execution:

- An instruction must work on stack operands and local variables of the correct type
- A method must use no more local variables and no more local stack positions than it claims to
- For every point in the bytecode, the local stack has the same depth whenever that point is reached
- A method must throw no more exceptions than it admits to
- The execution of a method must end with a return or throw instruction, not `fall off the end'
- Execution must not use one half of a two-word value (e.g. a long) as a one-word value (int)

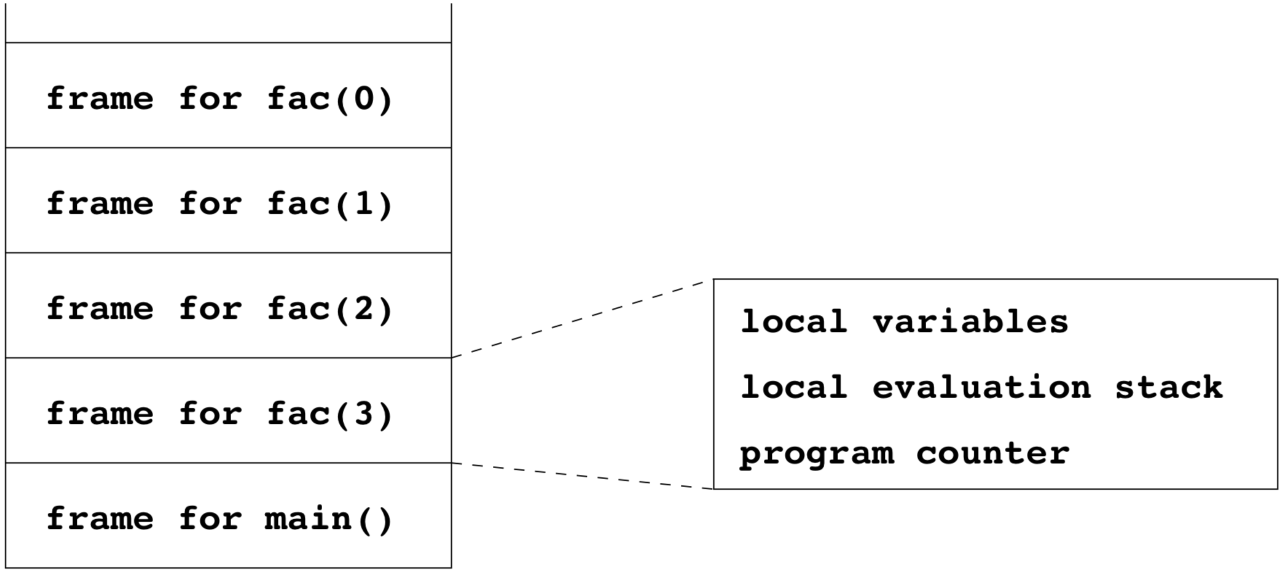
Additional JVM *runtime* checks

- Array-bounds checks on arr[i]
- Array assignment checks: Can store only subtypes of A into an A[] array
- Null-reference check (a reference is null *or* points to an object or array, because no pointer arithmetics)
- Checked casts: Cannot make arbitrary conversions between object classes
- Memory allocation succeeds or throws exception
- No manual memory deallocation or reuse

- Bottom line: A JVM program cannot read or overwrite arbitrary memory
- Better debugging, better security
- No buffer overflow attacks, worms, etc as in C/C++

The JVM runtime stacks

- One runtime stack per thread
  - Contains activation records, one for each active function call
  - Each activation record has program counter, local variables, and local stack for intermediate results



frame for fac(0)

frame for fac(1)

frame for fac(2)

frame for fac(3)

frame for main()

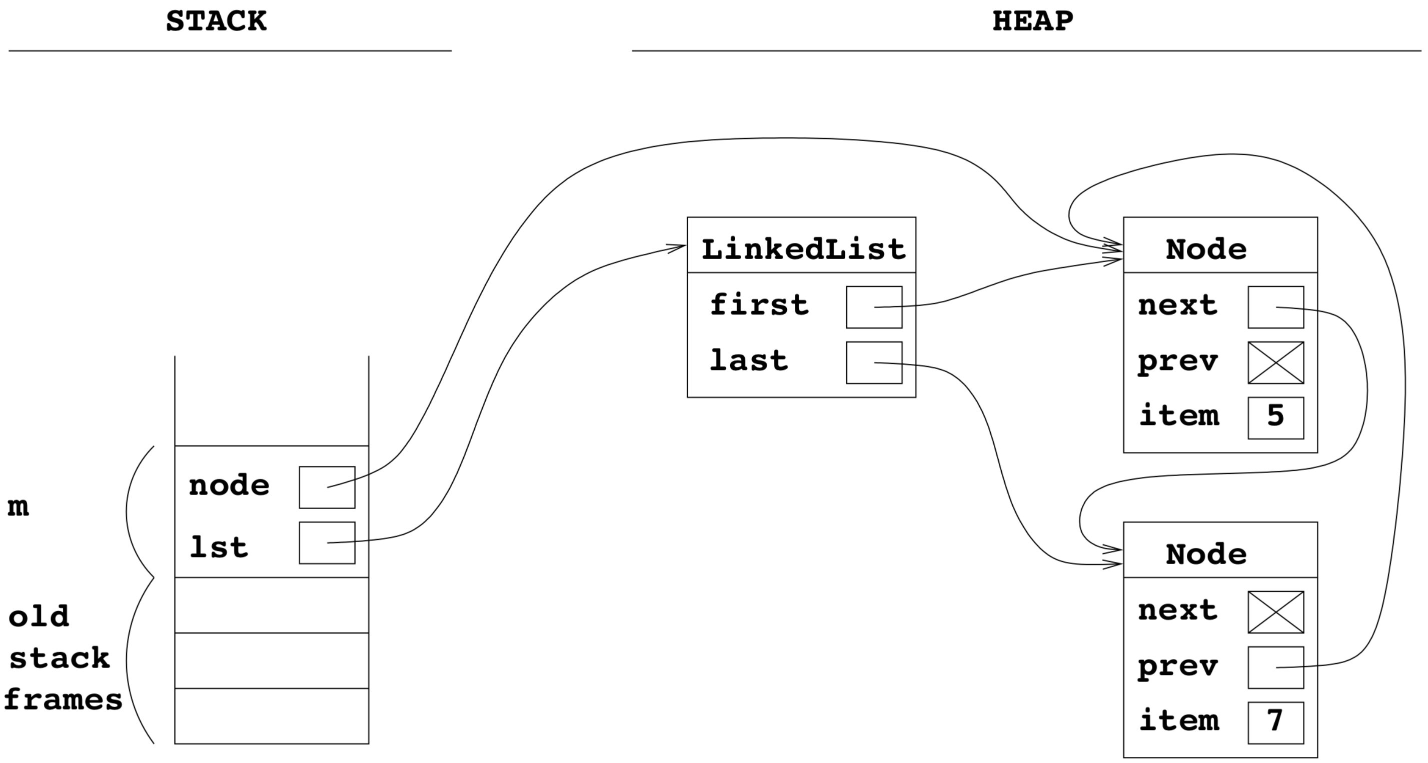
local variables

local evaluation stack

program counter

Example JVM runtime state

```
void m() {
  LinkedList lst = new LinkedList();
  lst.addLast(5);
  lst.addLast(7);
  Node node = lst.first;
}
```



The .NET Common Language Infrastructure (CLI, CLR)

- Same philosophy and design as JVM
- Some improvements:
  - Standardized bytecode assembly (text) format
  - Better versioning, strongnames, …
  - Designed as target for multiple source languages (C#, VB.NET, JScript, Eiffel, F#, Python, Ruby, …)
  - User-defined value types (structs)
  - Tail calls to support functional languages
  - True generic types in bytecode: safer, more efficient, and more complex
- The .exe file = stub + bytecode
- Standardized as Ecma-335

Some .NET CLI bytecode instructions

Kind	Example instructions
push constant	ldc.i4, ldc.r8, ldnull, ldstr, ldtoken
arithmetic	add, sub, mul, div, rem, neg; add.ovf, sub.ovf, …
load local variable	ldloc, ldarg
store local variable	stloc, starg
load array element	ldelem.i1, ldelem.i2, ldelem.i4, ldelem.r8
stack manipulation	pop, dup
load field	ldfld, ldstfld
method call	call, calli, callvirt
method return	ret
unconditional jump	br
conditional jump	brfalse, brtrue; beq, bge, bgt, ble, blt, …; bge.un …
object-related	newobj, isinst, castclass

Type suffixes: i1=byte, i2=short, i4=int, i8=long, r4=float, r8=double, …

From Java and C# to bytecode

- Consider the Java/C#/C program ex13:

```
static void Main(string[] args) {
  int n = int.Parse(args[0]);
  int y;
  y = 1889;
  while (y < n) {
    y = y + 1;
    if (y % 4 == 0 && (y % 100 != 0 || y % 400 == 0))
      InOut.PrintI(y);
  }
  InOut.PrintC(10);
}
```

- Let us compile and disassemble it twice:
  - `javac ex13.java` then `javap -c ex13`
  - `csc /o ex13.cs` then `ildasm /text ex13.exe`

JVM

.NET

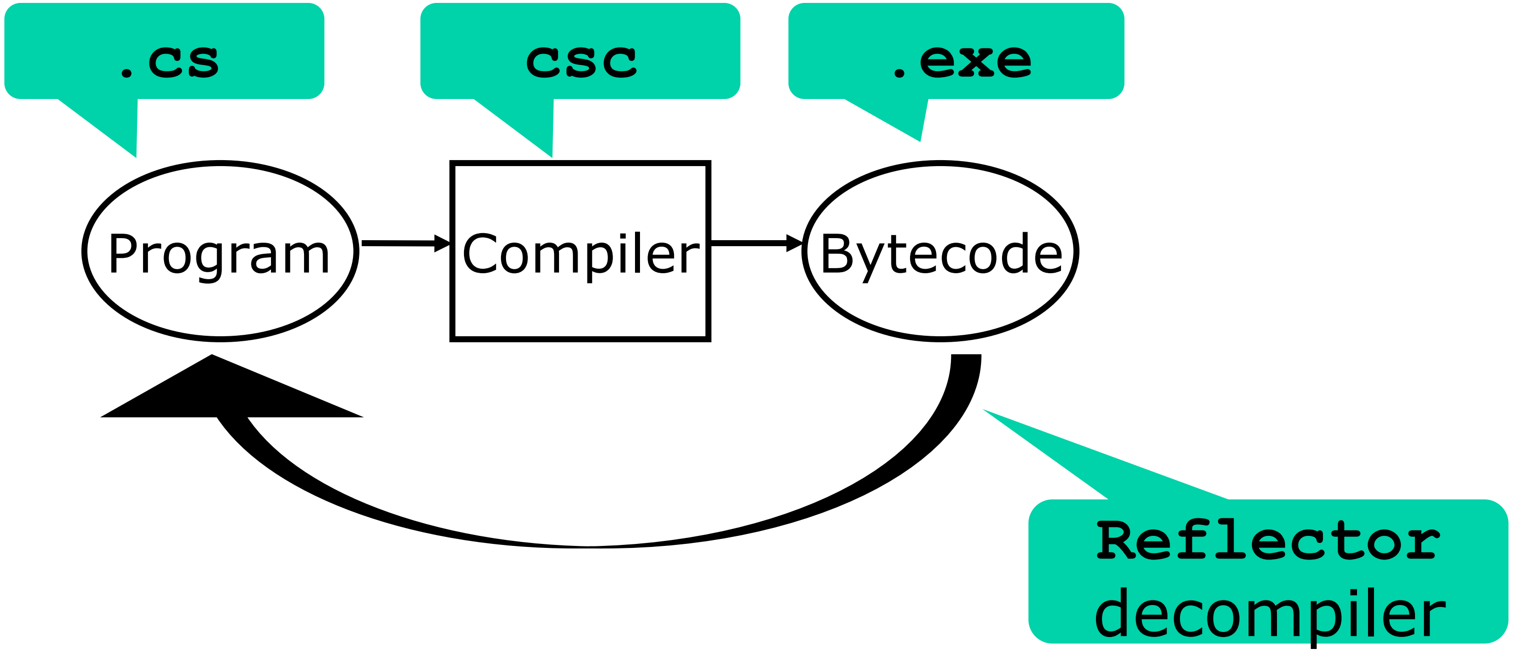
```
00 aload_0                    |      0000 ldarg.0
01 iconst_0                   |      0001 ldc.i4.0
02 aaload                     |      0002 ldelem.ref
03 invokestatic parseInt      |      0003 call Parse
06 istore_1                   |      0008 stloc.0
07 sipush 1889                |      0009 ldc.i4 0x761
10 istore_2                   |      000e stloc.1
11 iload_2                    |      000f br 003b
12 iload_1                    |      0014 ldloc.1
13 if_icmpge 48               |      0015 ldc.i4.1
16 iload_2                    |      0016 add
17 iconst_1                   |      0017 stloc.1
18 iadd                       |      0018 ldloc.1
19 istore_2                   |      0019 ldc.i4.4
20 iload_2                    |      001a rem
21 iconst_4                   |      001b brtrue 003b
22 irem                       |      0020 ldloc.1
23 ifne 11                    |      0021 ldc.i4.s 100
26 iload_2                    |      0023 rem
27 bipush 100                 |      0024 brtrue 0035
29 irem                       |      0029 ldloc.1
30 ifne 41                    |      002a ldc.i4 0x190
33 iload_2                    |      002f rem
34 sipush 400                 |      0030 brtrue 003b
37 irem                       |      0035 ldloc.1
38 ifne 11                    |      0036 call PrintI
41 iload_2                    |      003b ldloc.1
42 invokestatic printi        |      003c ldloc.0
45 goto 11                    |      003d blt 0014
48 bipush 10                  |      0042 ldc.i4.s 10
50 invokestatic printc        |      0044 call PrintC
53 return                     |      0049 ret
```

Ten-minute exercise

- On a printout of the preceding slide
- For both the JVM and the .NET columns
  - Draw arrows to indicate where jumps go
  - Draw blocks around the bytecode segments corresponding to expressions and statements in the ex13.java and ex13.cs programs

Metadata and decompilers

- The .class and .exe files contains *metadata*: names and types of fields, methods, classes
- One can *decompile* bytecode into programs:



- Bad for protecting your secrets (intellectual property)
- *Bytecode obfuscators* make decompilation harder

.NET CLI has generic types, JVM doesn’t

```
class CircularQueue<T> {
  private readonly T[] items;
  public CircularQueue(int capacity) {
    this.items = new T[capacity];
  }
  public T Dequeue() { ... }
  public void Enqueue(T x) { ... }
}
```

Source; generics

```
.class CircularQueue`1<T> ... {
  .field private initonly !T[] items
  ...
  .method !T  Dequeue() { ... }
  .method void Enqueue(!T x) { ... }
}
```

.NET CLI; generics

```
class CircularQueue ... {
  public java.lang.Object dequeue(); ...
  public void enqueue(java.lang.Object); ...
}
```

JVM; **no** generics

Consequences for Java

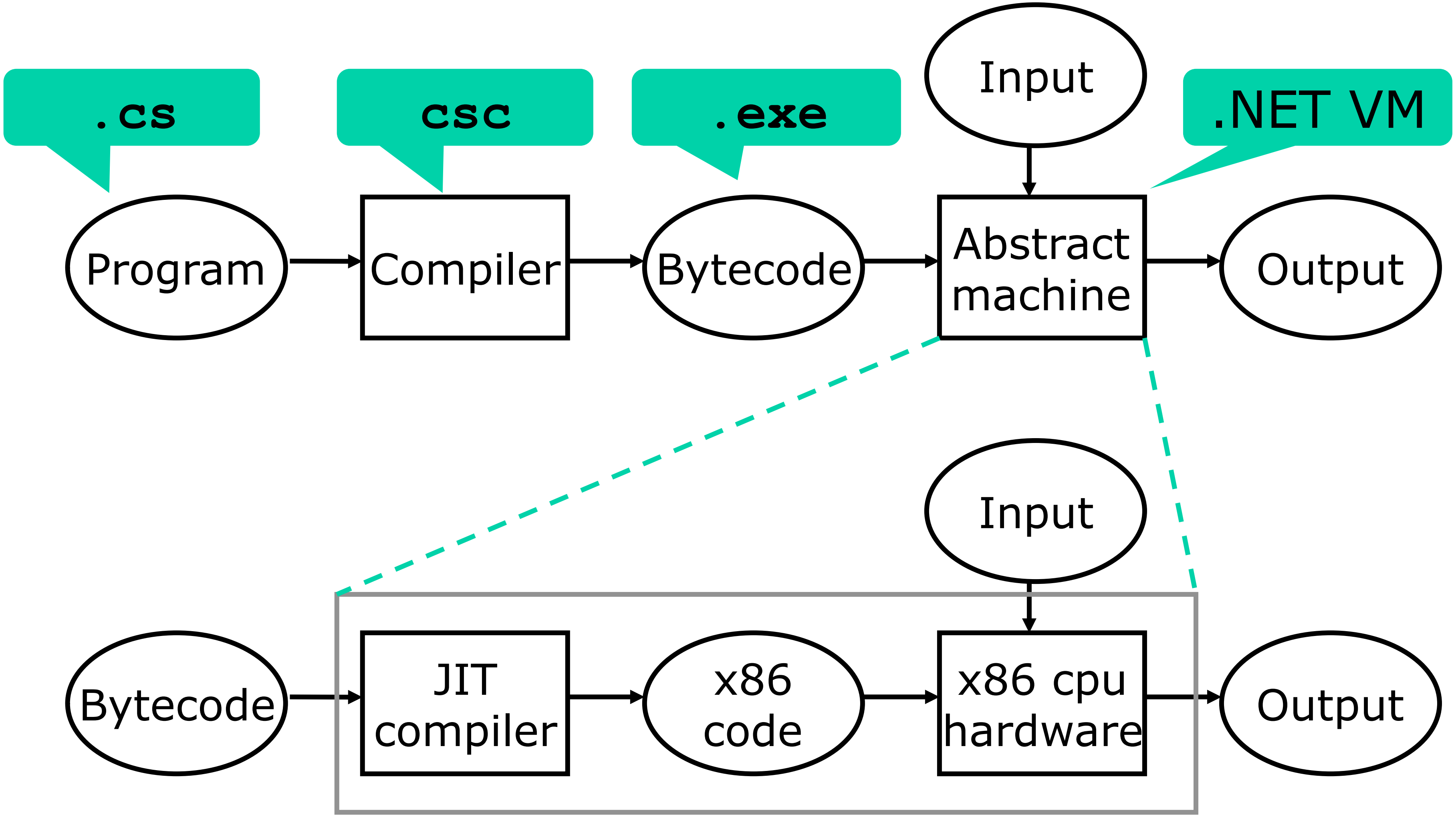
- The Java compiler replaces T
  - with **`Object`** in **`C<T>`**
  - with **`Mytype`** in **`C<T extends Mytype>`**
- So this **doesn't work** in Java, but works in C#:
  - Cast: **`(T)e`**
  - Instance check: **`(e instanceof T)`**
  - Reflection: **`T.class`**
  - Overload on different type instances of gen class:

```
void put(CircularQueue<Double> cqd) { ... }
void put(CircularQueue<Integer> cqd) { ... }
```

  - Array creation: **`arr=new T[10]`**
    So Java versions of CircularQueue<T> must use ArrayList<T>, not T[]

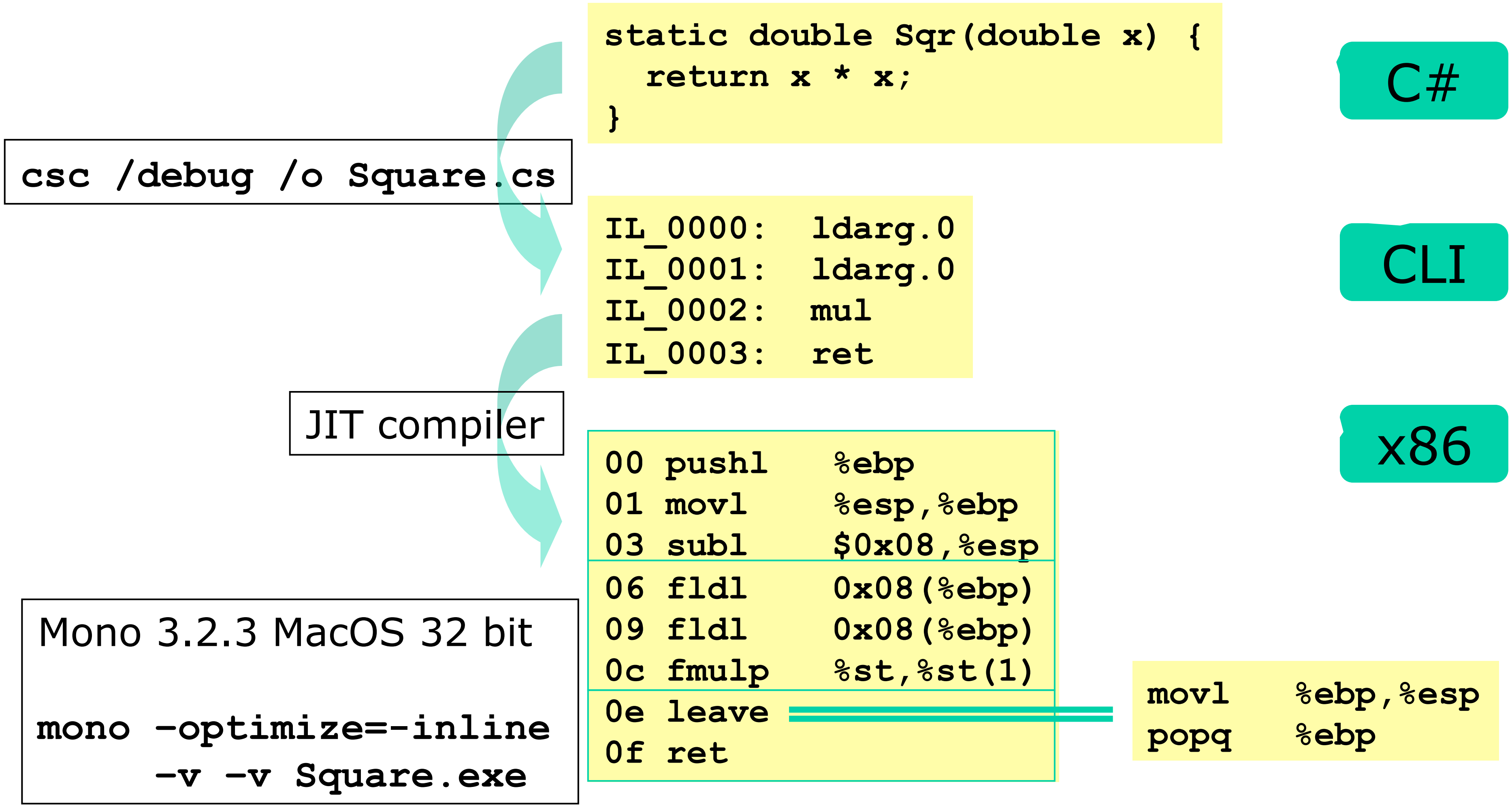
Just-in-time (JIT) compilation

- Bytecode is compiled to real (e.g. x86) machine code at runtime to get speed comparable to C/C++



Just-in-time compilation

- How to inspect .NET JITted code



```
static double Sqr(double x) {
  return x * x;
}
```

C#

```
csc /debug /o Square.cs
```

```
IL_0000:   ldarg.0
IL_0001:   ldarg.0
IL_0002:   mul
IL_0003:   ret
```

CLI

JIT compiler

```
00 pushl    %ebp
01 movl     %esp,%ebp
03 subl     $0x08,%esp
06 fldl     0x08(%ebp)
09 fldl     0x08(%ebp)
0c fmulp    %st,%st(1)
0e leave
0f ret
```

x86

```
movl    %ebp,%esp
popq    %ebp
```

Mono 3.2.3 MacOS 32 bit

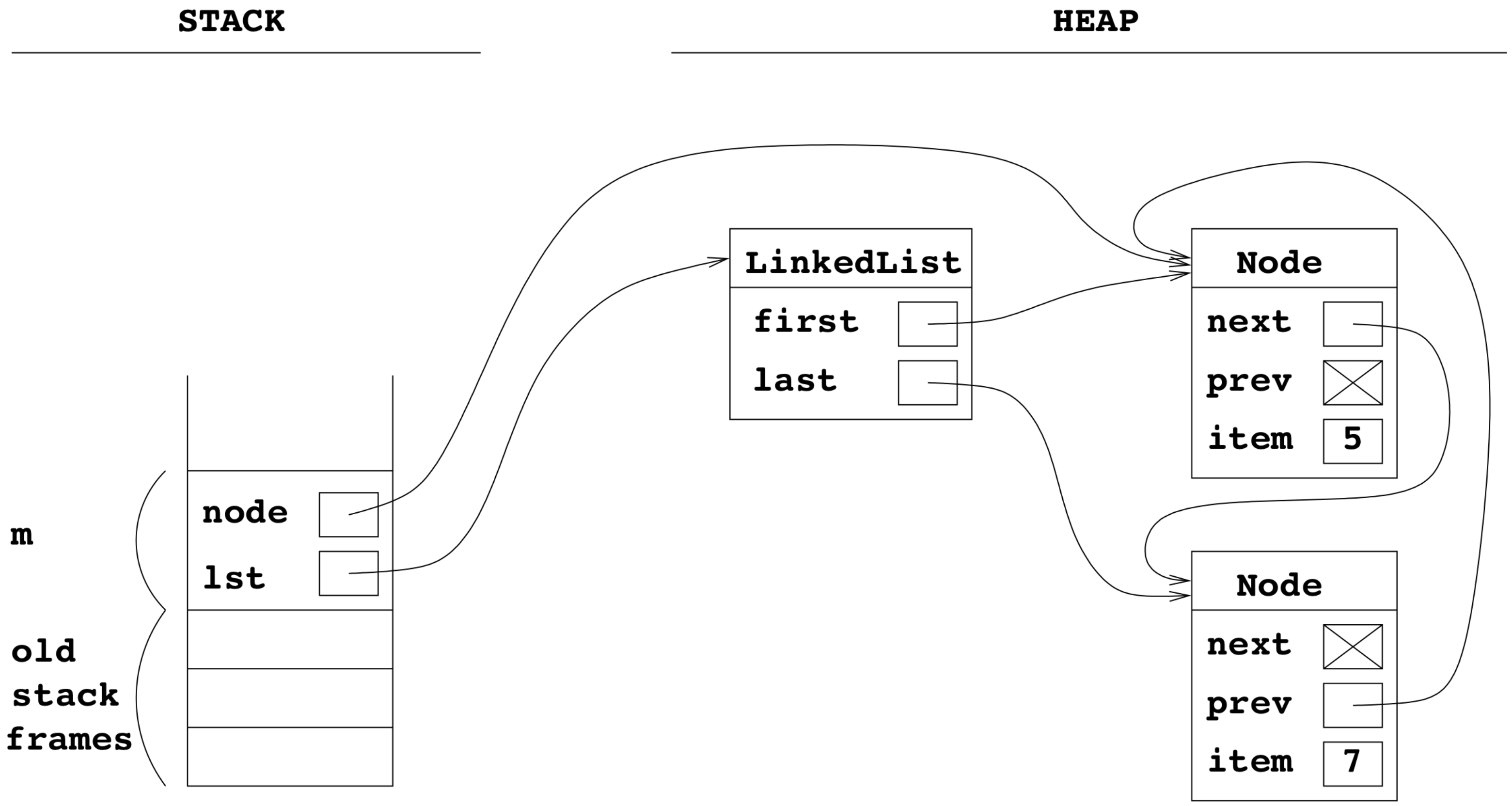
```
mono -optimize=-inline
     -v -v Square.exe
```

Garbage collection

- A: Reference counting
- B: Mark-sweep
- C: Two-space stop-and-copy, compacting
- D: Generational
- Conservative

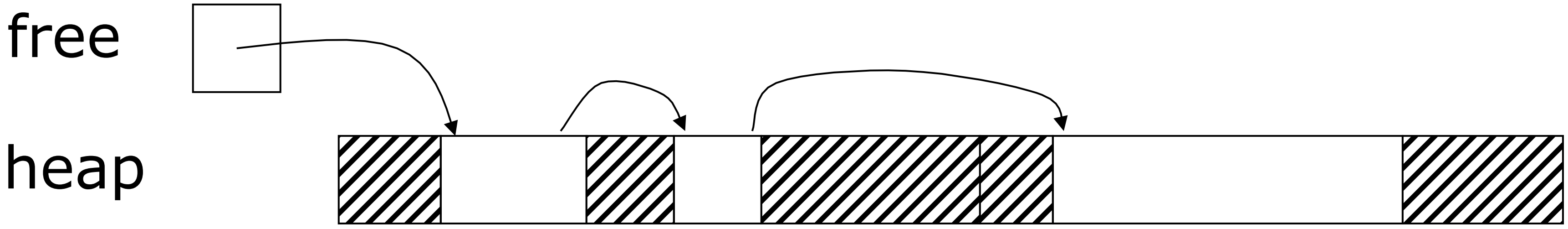
The heap as a graph

- The heap is a *graph*: node=object, edge=reference
- An object is *live* if reachable from *roots*
- Garbage collection *roots* = stack elements



The freelist

- A freelist is a linked list of free heap blocks:



▨ live
☐ free
▦ dead

- Allocation from freelist:
  - Search for a large enough free block
  - If none found, do garbage collection
  - Try the search again
  - If it fails, we are out of memory

A: Reference counting with freelist

- Each object knows the number of references to it
- Allocate objects from the freelist
- After assignment **`x=o;`** the runtime system
  - Increments the count of object o
  - Decrements the count of x’s old reference (if any)
  - If that count becomes zero,
    - put that object on the freelist
    - recursively decrement count of all objects it points to
- Good
  - Simple to implement
- Bad
  - Reference count field takes space in every object
  - Reference count updates and checks take time
  - A cascade of decrements takes long time, gives long pause
  - Cannot deallocate cyclic structures

B: Mark-sweep with freelist

- Allocate objects from the freelist
- GC phase 1: mark phase
  - Assume all objects are white to begin with
  - Find all objects that are reachable from the stack, and color them black
- GC phase 2: sweep phase
  - Scan entire heap, put all white objects on the freelist, and color black objects white
- Good
  - Rather simple to implement
- Bad
  - Sweep must look at entire heap, also dead objects; inefficient when many small objects die young
  - Risk of *heap fragmentation*

C: Two-space stop and copy

- Divide heap into to-space and from-space
- Allocate objects in from-space
- When full, recursively move all reachable objects from from-space to the empty to-space
- Swap (empty) from-space with to-space
- Good
  - Need only to look at live objects
  - Good reference locality and cache behavior
  - Compacts the live objects: no fragmentation
- Bad
  - Uses twice as much memory as maximal live object size
  - Needs to update references when moving objects
  - Moving a large object (e.g. an array) is slow
  - Very slow (much copying) when heap is nearly full

D: Generational garbage collection

- Observation: Most objects die young
- Divide heap into *young* (nursery) and *old* generation
- Allocate in young generation
- When full, move live objects to old gen. (minor GC)
- When old gen. full, perform a (major) GC there
- Good
  - Recovers much garbage fast
- Bad
  - May suffer fragmentation of old generation (if mark-sweep)
  - Needs a write barrier test on field assignments:
    After assignment **`o.f=y`** where **`o`** in old and **`y`** in young,
    need to remember that **`y`** is live

Conservative garbage collectors

- Is 0xFFFFFFFA on the stack an int or a heap ref?
- If the GC doesn’t know, it must be *conservative*: Assume it could be a reference to an object
- Conservative collectors exist as C/C++ libraries

- Good
  - Can be added to C and C++ programs as a library
  - Works even with pointer arithmetics
- Bad
  - Unpredictable memory leaks
  - Cannot be compacting: updating a “reference” that is actually a customer number leads to madness

Concurrent garbage collection

- In a multi-cpu machine, let one cpu run GC
- Complicated
  - Race conditions when allocating objects
  - Race conditions when moving objects
- Typically suspends threads at "GC safe" points
  - May considerably reduce concurrency (because one thread may take long to reach a safe point)

GC in mainstream virtual machines

- Sun/Oracle Hotspot JVM (client+server)
  - Three generations
  - When gen. 0 is full, move live objects to gen. 1
  - Gen. 1 uses two-space stop-and-copy GC; when objects get old they are moved to gen. 2
  - Gen. 2 uses mark-sweep with compaction
- IBM JVM (used in e.g. Websphere server)
  - Highly concurrent generational; see David Bacon's paper
- Microsoft .NET (desktop+server)
  - Three generation small-obj heap + large-obj heap
  - When gen. 0 is full, move to gen. 1
  - When gen. 1 is full, move to gen. 2
  - Gen. 2 uses mark-sweep with occasional compaction
- Mono .NET implementation
  - Boehm's conservative collector (still standard May 2012)
  - New two-generational (stop-and-copy plus M-S or S-&-C)

Other GC-related topics

- *Large object space*: Large arrays and other long-lived objects may be stored separately
- *Weak reference*: A reference that cannot itself keep an object live
- *Finalizer*: Code that will be executed when an object dies and gets collected (e.g. close file)
- *Resurrection*: A finalizer may make a dead object live again (yrk!)
- *Pinning*: When Java/C# exports a reference to C/C++ code, the object must be pinned; if GC moves it, the reference will be wrong

GC stress (StringConcatSpeed.java)

- What do these loops do? Which is better?

```
StringBuilder buf
  = new StringBuilder();
for (int i=0; i<n; i++)
  buf.append(ss[i]);
res = buf.toString();
```

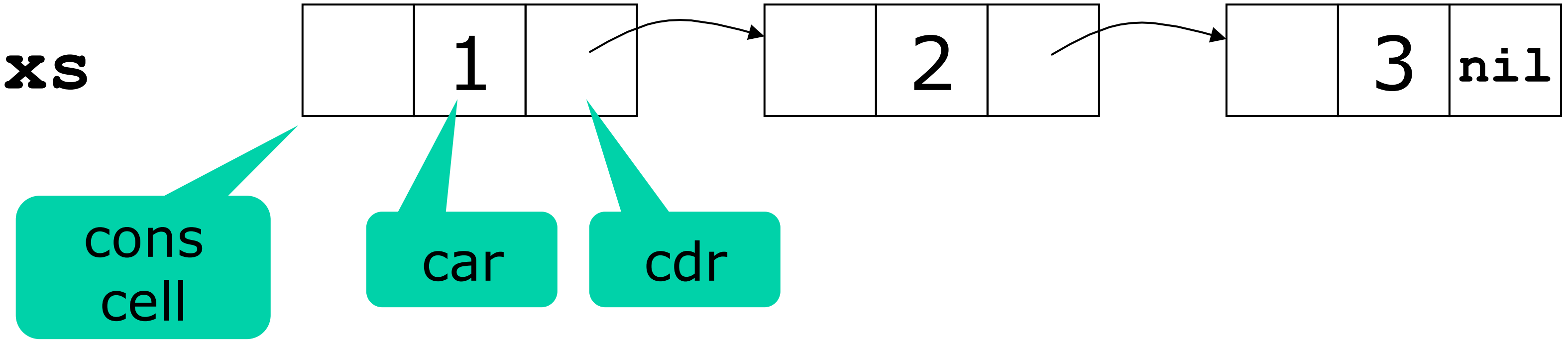
```
String res = "";
for (int i=0; i<n; i++)
  res += ss[i];
```

New: List-C and the list machine

- list-c = micro-C with Lisp/Scheme data

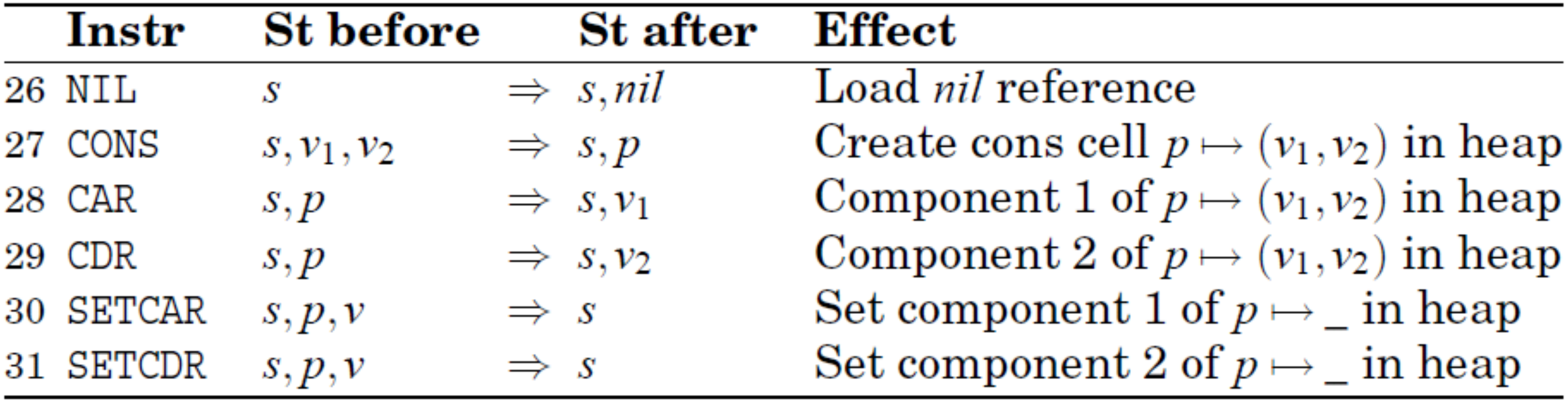
```
void main(int n) {
  dynamic xs;
  xs = nil;
  while (n>0) {
    xs = cons(n,xs);
    n = n - 1;
  }
  printlist(xs);
}
```

```
void printlist(dynamic xs) {
  while (xs) {
    print car(xs);
    xs = cdr(xs);
  }
}
```



List machine instructions

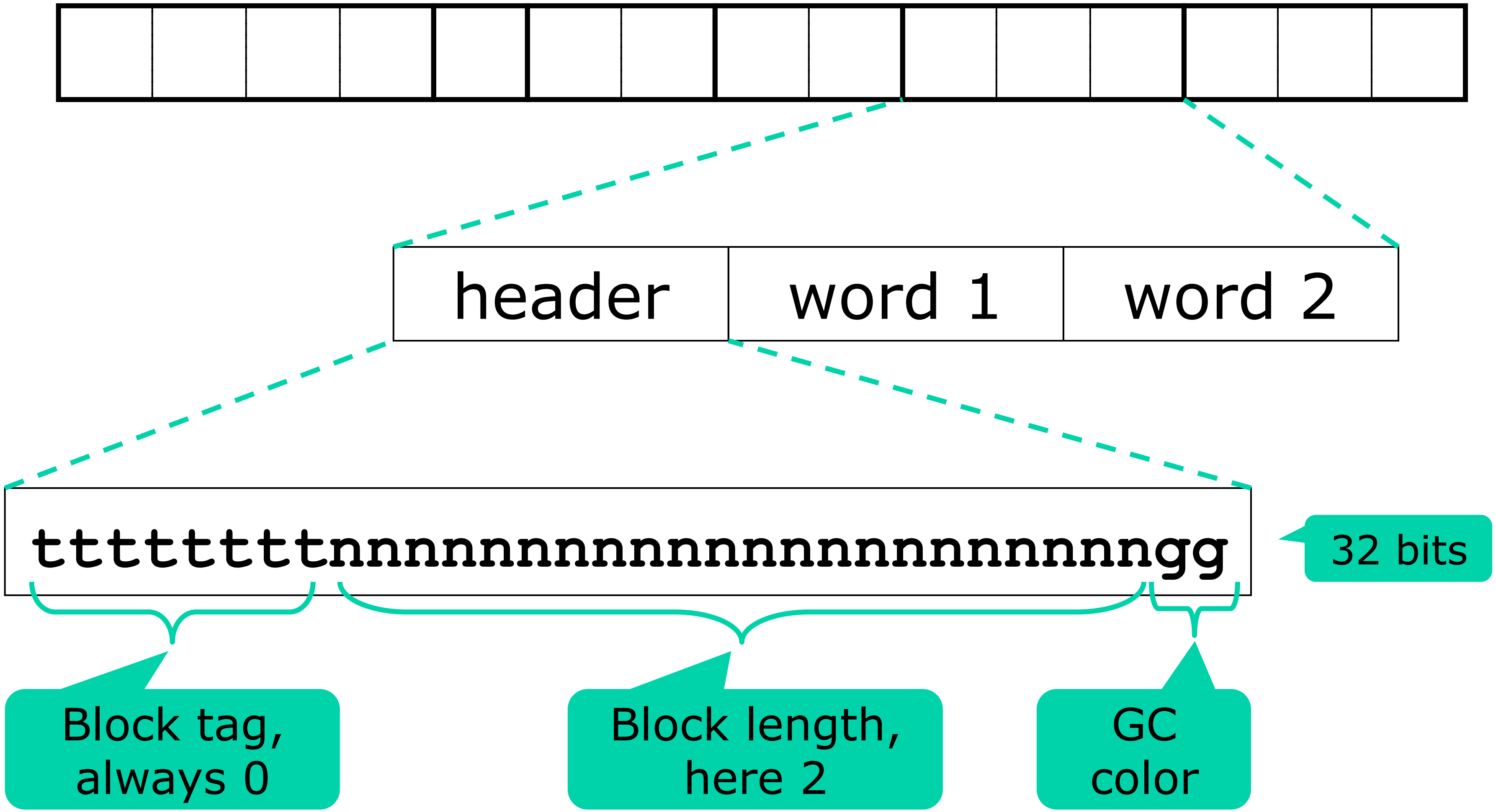
- List machine = micro-C abstract machine plus six extra instructions:
  - NIL: Put nil reference on stack
  - CONS: Allocate two-word block on heap, put reference to it on stack
  - CAR, CDR: Access word 1 or 2 of block
  - SETCAR, SETCDR: Set word 1 or 2 of block



	Instr	St before		St after	Effect
26	NIL	s	$\Rightarrow$	s, nil	Load *nil* reference
27	CONS	s, v_1, v_2	$\Rightarrow$	s, p	Create cons cell $p \mapsto (v_1, v_2)$ in heap
28	CAR	s, p	$\Rightarrow$	s, v_1	Component 1 of $p \mapsto (v_1, v_2)$ in heap
29	CDR	s, p	$\Rightarrow$	s, v_2	Component 2 of $p \mapsto (v_1, v_2)$ in heap
30	SETCAR	s, p, v	$\Rightarrow$	s	Set component 1 of $p \mapsto \_$ in heap
31	SETCDR	s, p, v	$\Rightarrow$	s	Set component 2 of $p \mapsto \_$ in heap

The structure of the list machine heap

- The heap consists of 32-bit (4-byte) *words*
- The heap is covered by *blocks*



header

word 1

word 2

ttttttttnnnnnnnnnnnnnnnnnnnnnngg

32 bits

Block tag, always 0

Block length, here 2

GC color

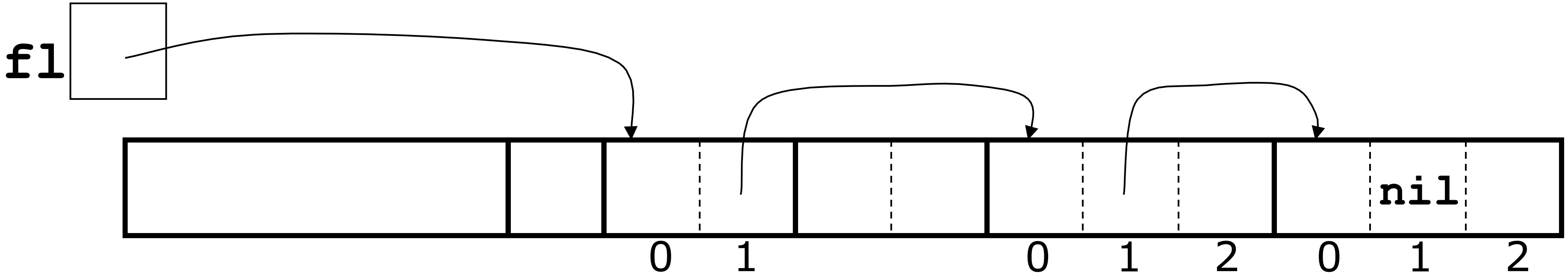
Garbage collection bits gg

Bits	Color	Meaning
00	white	After mark phase: Not reachable from stack; may be collected
01	grey	During mark phase: Reachable, referred-to blocks not yet marked
10	black	After mark phase: Reachable from stack; cannot be collected
11	blue	On freelist, or is orphan block

- The *mark phase* paints all reachable blocks black
- The *sweep phase* paints black blocks white; paints white blocks blue and puts them on freelist

The freelist; orphans

- All blocks on the freelist are blue (gg=11)
- Word 1 contains a reference to the next freelist element, or nil:



- A block of length zero is an *orphan*
- It consists of a header only
- (Created by allocating almost all of a block)
- Cannot be on freelist: no room for next ref.

Distinguishing integers and references

- For *exact* garbage collection we need to distinguish integers from references
- Old trick:
  - Make all heap blocks begin on address that is a multiple of 4; in binary it has form xxxxxx00
  - Represent integer n as 2n+1, so the integer's representation has form xxxxxxx1
- Test for IsInt(v): **`(v)&1==1`**
- Tagging an int: **`((v)<<1)|1`**
- Untagging an int: **`(v)>>1`**

An example list-C program, ex30.lc

- Each iteration allocates a cons cell that dies
- Without a garbage collector the program soon runs out of memory

```
void main(int n) {
  dynamic xs;
  while (n>0) {
    xs = cons(n, 22);
    print car(xs);
    n = n - 1;
  }
}
```

Allocate cons cell in heap

Assignment causes previous xs value to die

- Your task in BOSC: Implement garbage collectors: mark-sweep, and stop-and-copy

Reading and homework

- This week's lecture:
  - PLC chapters 9 and 10
  - Sun Microsystems: Memory Management in the Java Hotspot Virtual Machine
  - David Bacon, IBM: Realtime garbage collection
  - Exercise 9.1, and either exercise 9.2 (but many have problems with perfmon) or exercise 9.3 on next slide

- Next week's lecture:
  - PLC chapter 11

Alternative exercise 9.3

```
class SentinelLockQueue implements Queue {
  private static class Node {
    final int item;
    volatile Node next;
    public Node(int item, Node next) {
      this.item = item;
      this.next = next;
    }
  }
  private final Node dummy = new Node(-444, null);
  private Node head = dummy, tail = dummy;
  public synchronized boolean put(int item) {
    Node node = new Node(item, null);
    tail.next = node;
    tail = node;
    return true;
  }
  public synchronized int get() {
    if (head.next == null)
      return -999;
    Node first = head;
    head = first.next;
    return head.item;
  }
}
```

- Class SentinelLockQueue contains a memory management problem
- Run it and see what happens
- Find out what the problem is, explain it, and fix it
- The corrected code should run to completion without error
- Source code and more explanation is in file QueueWithMistake.java