Compiler Construction

Lecture 12: garbage collection

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Memory management

Manual memory management: programmer controls (de)allocation time/place:

```
void *malloc(size_t n)    /* allocate n bytes, return address */
void free(void *addr)     /* relinquish use of memory at addr */
```

The programmer has a lot of control. However, mistakes can be disastrous:

missing free

```
p = malloc(10);
return OK;
```

double free

```
free(p);
free(p);
```

use after free

```
free(p);
*p += 1;
```

(Observation: deallocation is much harder than allocation)

Many programming languages support heap allocation
but do not provide a deallocation operation

```
d = dict(x=3,y=4)
```

Python

```
let d = [("x",3); ("y",4)]
```

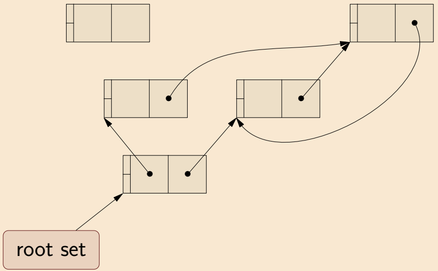
OCaml

Unless the storage is reclaimed *somehow*, memory might be exhausted.

General approach: **automatic memory management** (“garbage collection”)

Automation is based on an approximation:

If data can be reached from a **root set**, *then* it is not "garbage"



The root set might include: the stack, registers, global variables.

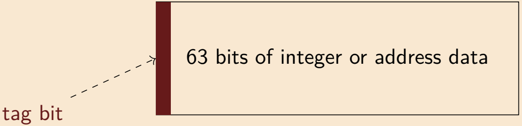
(Without loss of generality, assume a *single root*)

Reachability and representations

Ascertaining reachability requires knowledge of representations:

What is a pointer?

(typical approach: use a *tag bit* to distinguish between pointers and integers)



How are objects laid out?

(typical approach: use *headers* that carry sizes and other metadata)

Reference counting

Reference counting & tracing collection

Two basic approaches (and many variations):

Reference counting

Keep a **reference count** with each object that represents the number of pointers to it.

An object is **garbage when its count is 0**

Tracing garbage collection

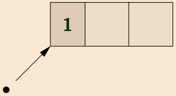
Keep alive objects **reachable** from the root set (i.e. transitive close of pointer graph)

An object is **garbage when it is unreachable**

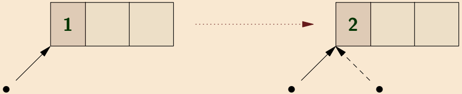
Reference counting: idea

The **reference count** tracks the number of pointers to each object.

An object's reference count is 1 when the object is created:



The count is incremented when a pointer newly references the object:

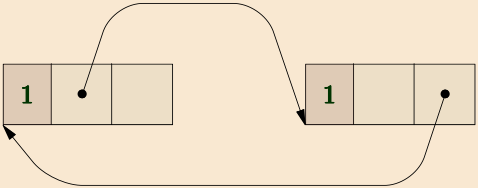


The count is decremented when a pointer no longer references the object:

The object is unreachable garbage when the reference count goes to 0:

Reference counting can't collect cyclic garbage

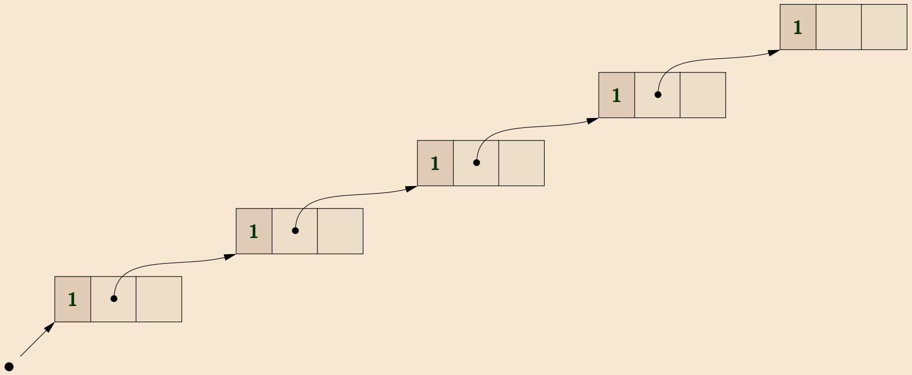
A **significant weakness** of reference counting:



There are no other references to these objects in the program but **the objects will never be collected**.

Long chains of objects make reclamation expensive

A **significant weakness** of (naive) reference counting:



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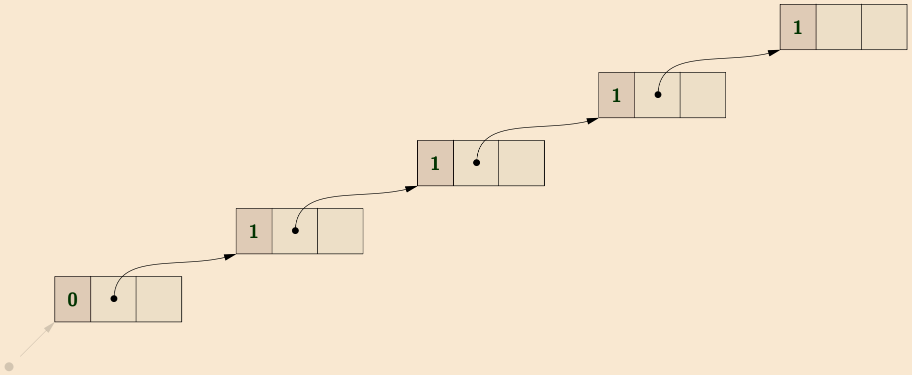

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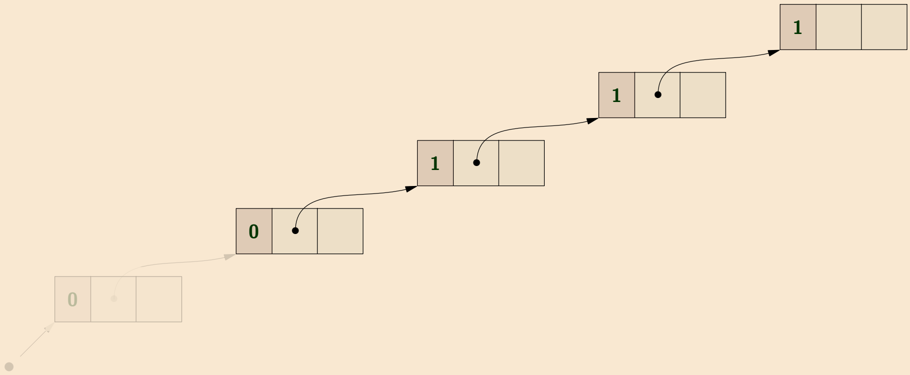

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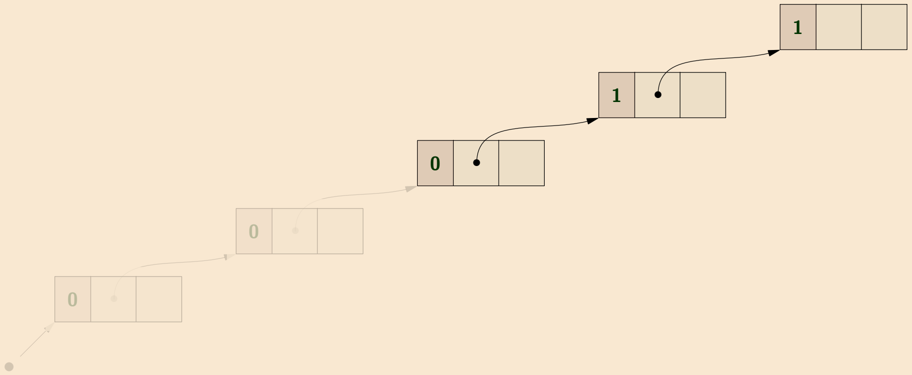

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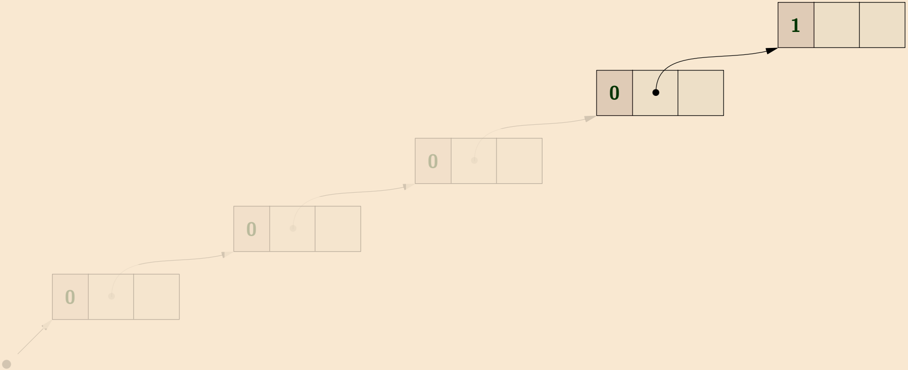

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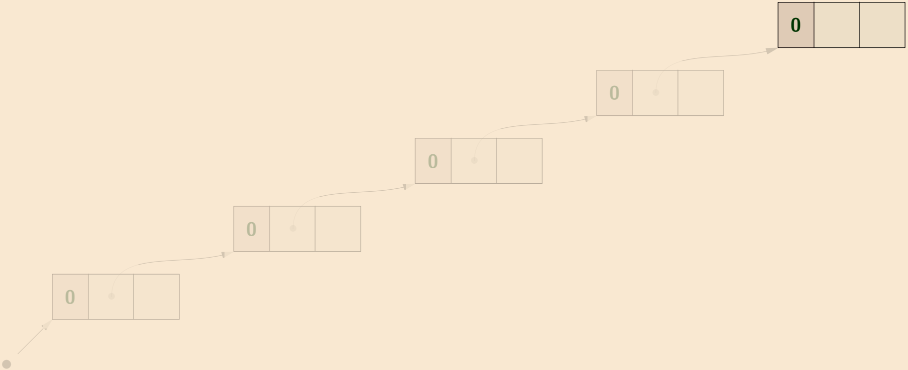


Reclaiming an object can set off an unboundedly large **chain of reclamations**

Reference counting: advantages and drawbacks

Advantages of reference counting:

+ Collection costs distributed through the computation
+ Allows rapid reclamation and immediate reuse

Drawbacks of reference counting:

– size overhead of storing references
– potentially high/unbounded cost on reclamation
– taking a reference involves (potentially expensive) mutation

Mark & sweep

Mark & sweep is a two-phase algorithm:

Mark phase: Traverse object graph depth first to **mark live data**

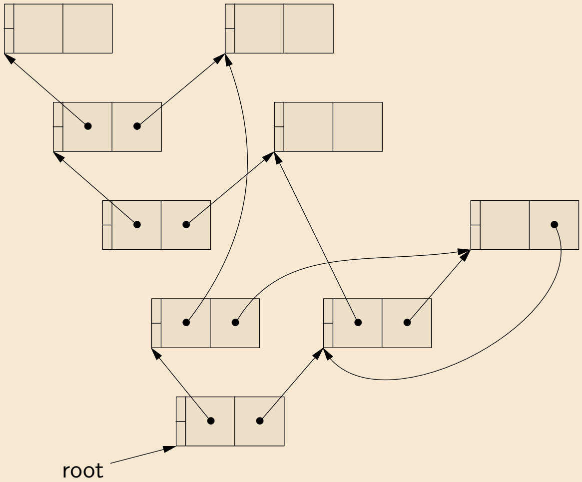
Sweep phase: iterate over entire heap, reclaiming unmarked data

Key idea: identify and reclaim **dead objects**

Marking

Mark

```
mark(node) =
  if not node.marked:
    node.marked = True
    for c in node.children:
      mark(c)
```



Memory
Reference counting
Mark & sweep
Copying
Generations

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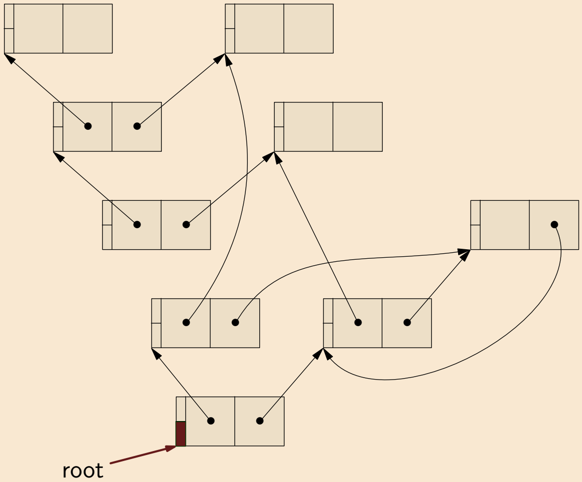

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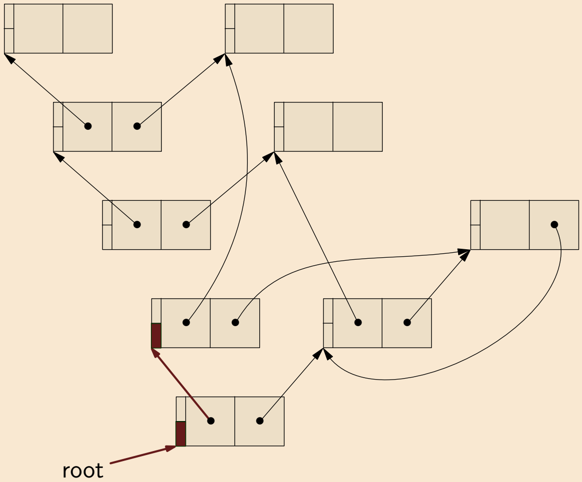

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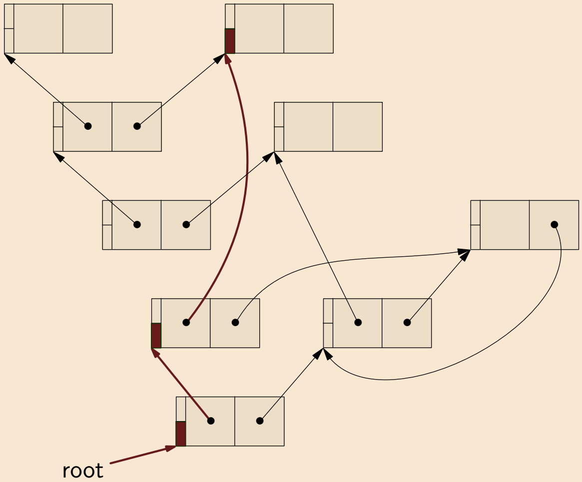

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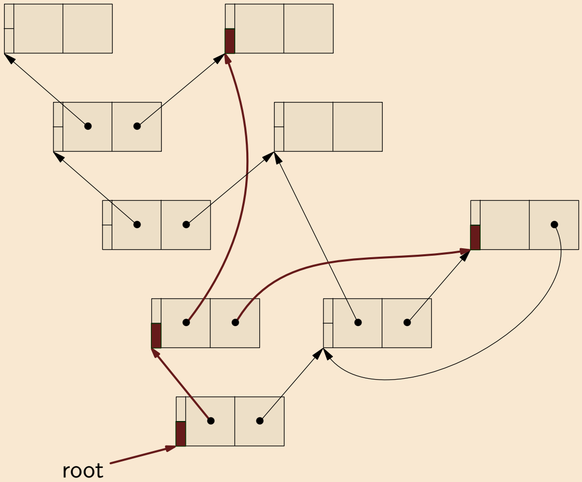

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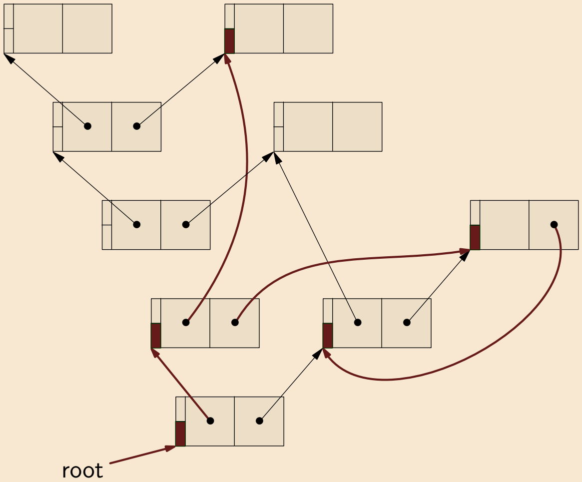

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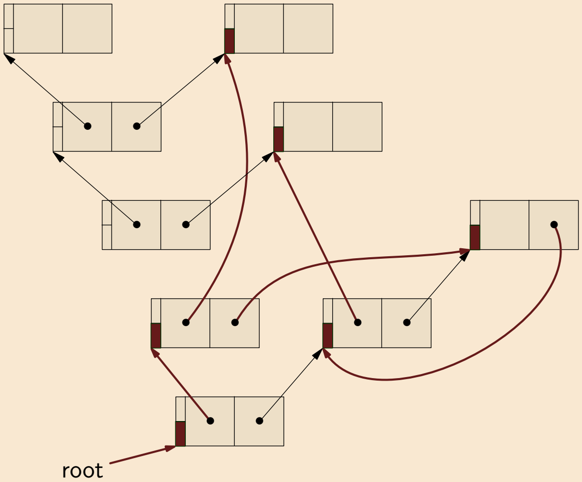

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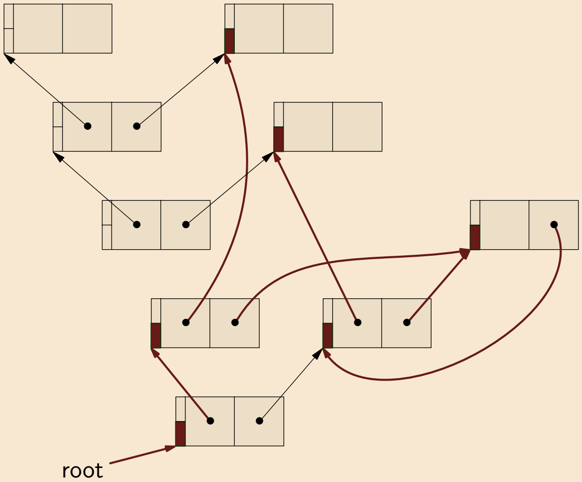

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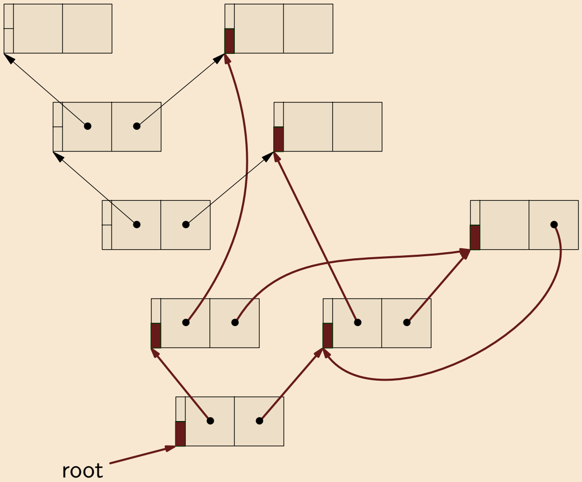


Memory

Reference counting

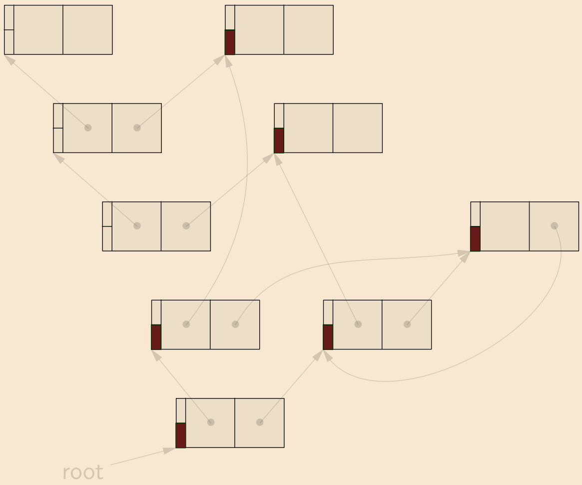
Mark & sweep

Copying

Generations

Sweep

- **linearly scan** through the heap
- **collect unmarked** blocks
- **unmark marked** blocks



Sweeping

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collect unmarked blocks

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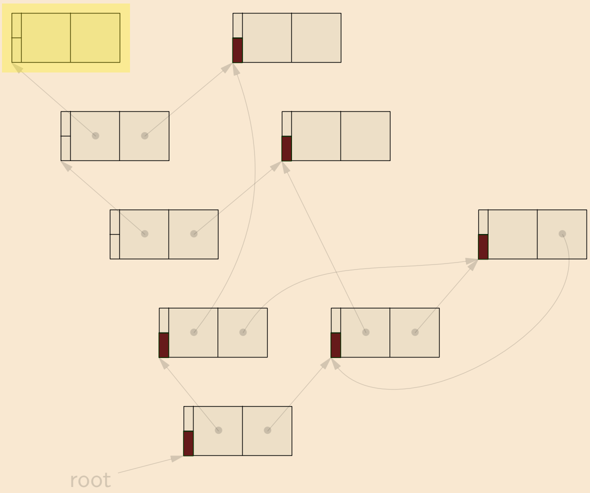

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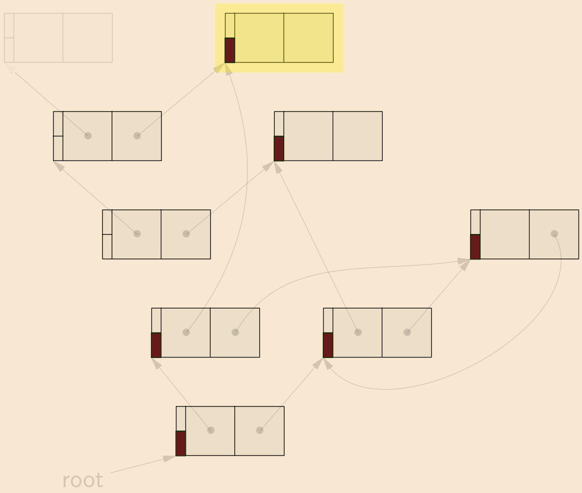

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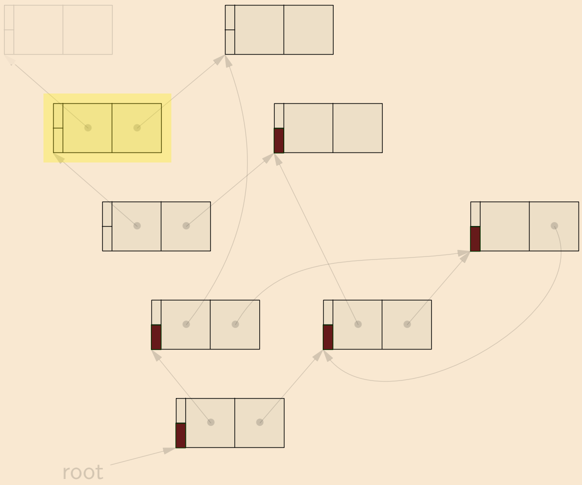

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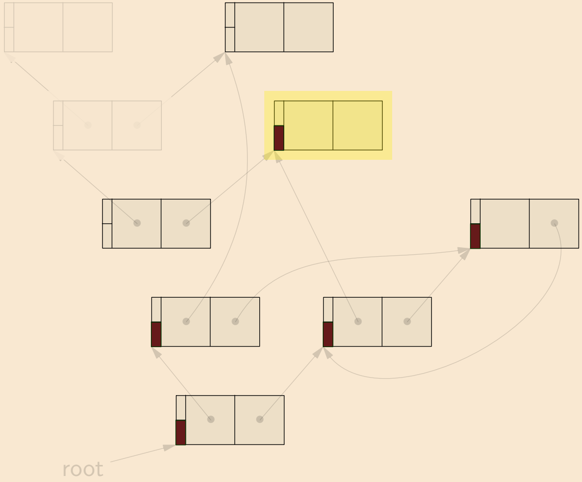

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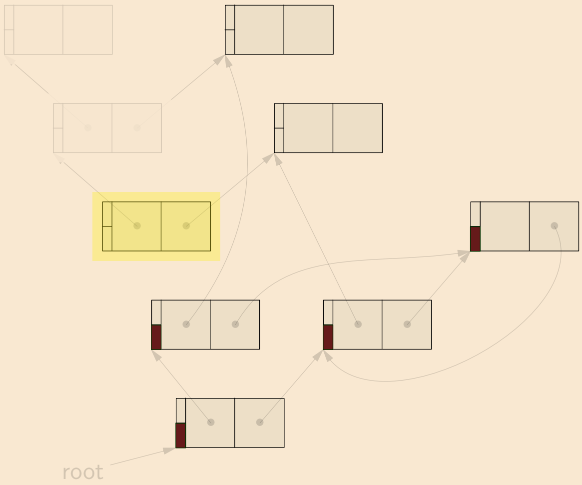

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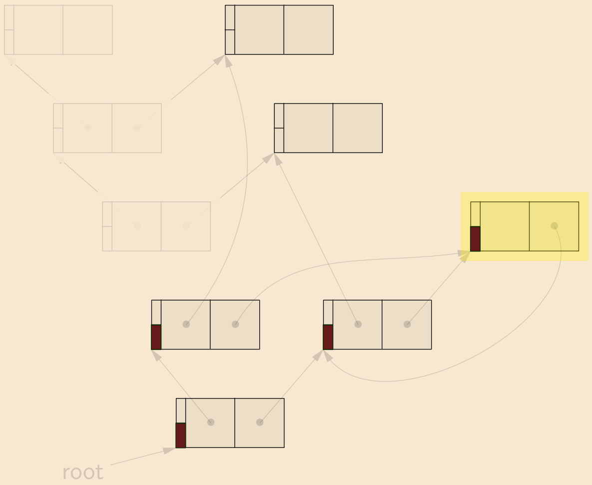

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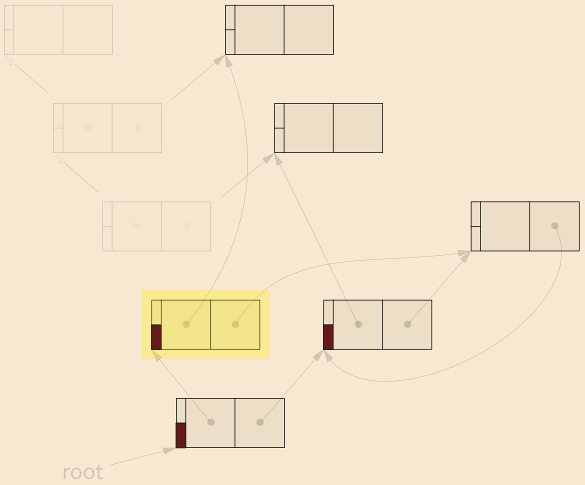

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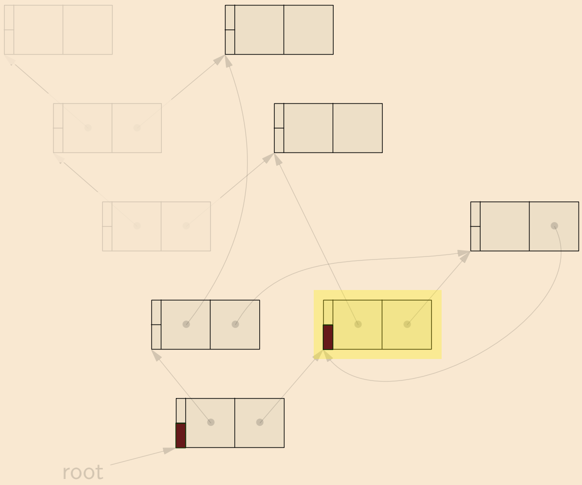

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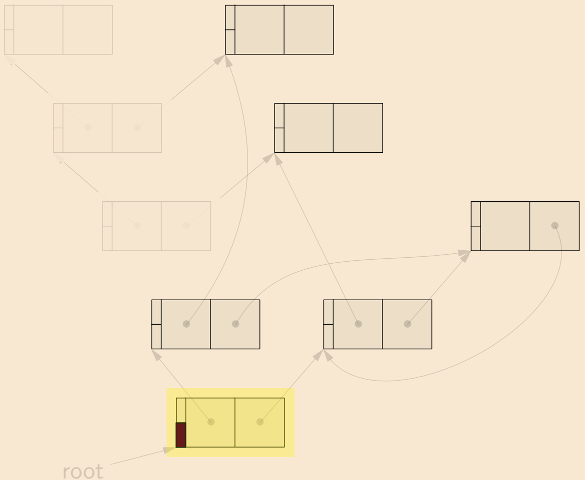

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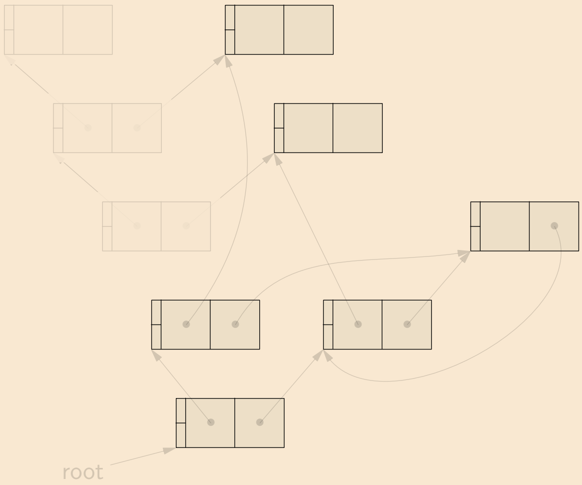
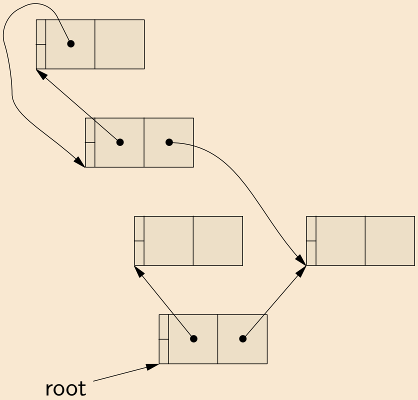


Mark & sweep is able to collect cyclic garbage:



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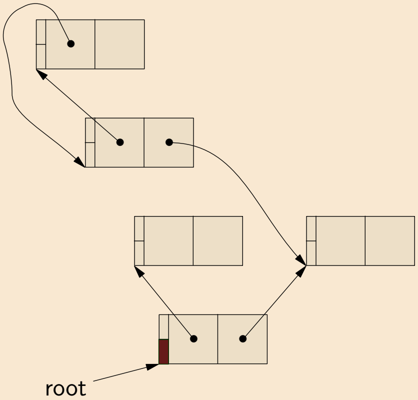

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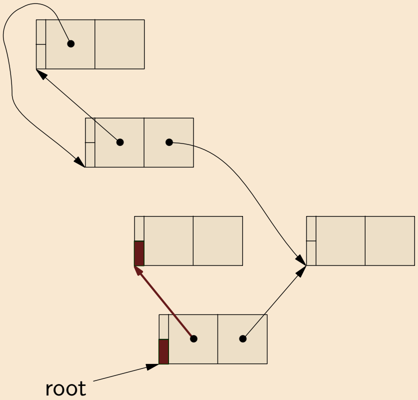

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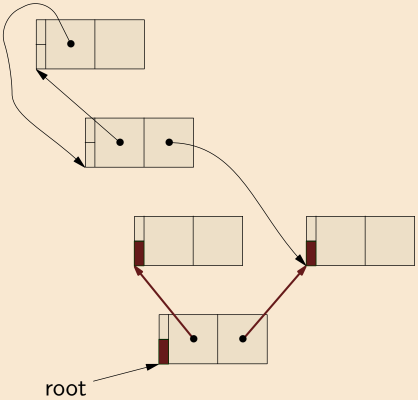

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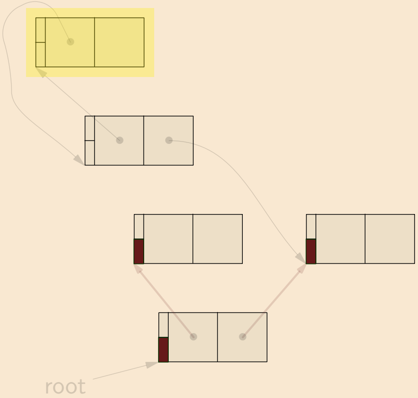

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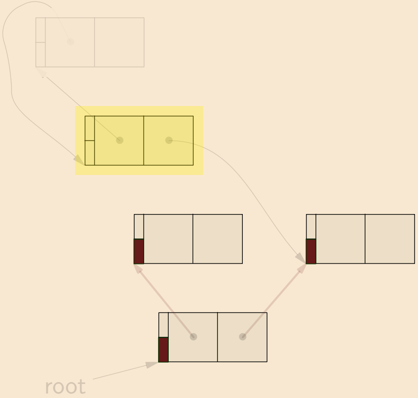

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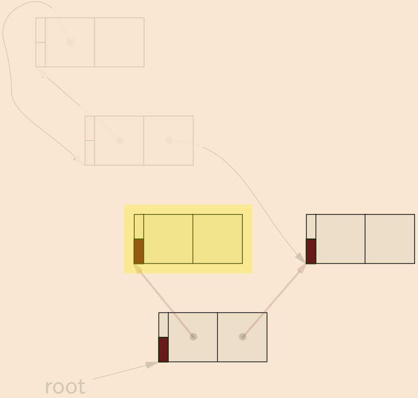

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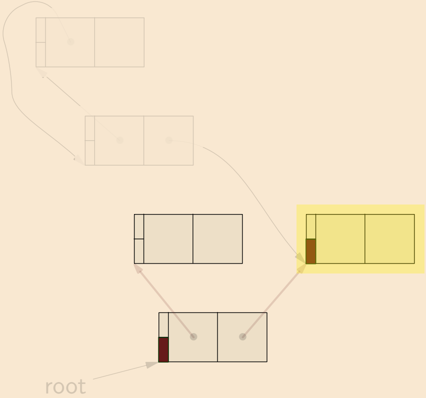

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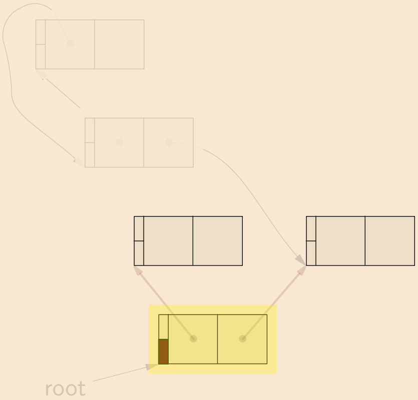

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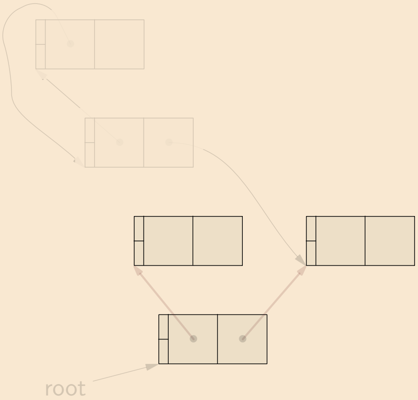


Mark & sweep: advantages and drawbacks

Advantages of mark & sweep:

+ Reasonably simple
+ Collects cycles
+ Low space overhead

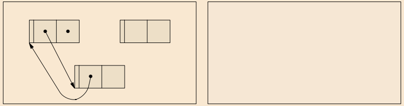
Drawbacks of mark & sweep

- Scans entire heap during sweeping
- Long (multi-second) pauses, inappropriate for interactive applications

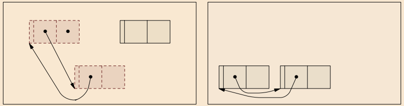
Copying collection

Copying collection: overview

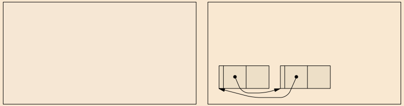
Split heap in two: **from-space** (active), **to-space** (unused)



During garbage collection: **copy** from from-space into to-space



After garbage collection: **abandon** dead objects, switch heap roles



Key idea: identify and move **live objects**

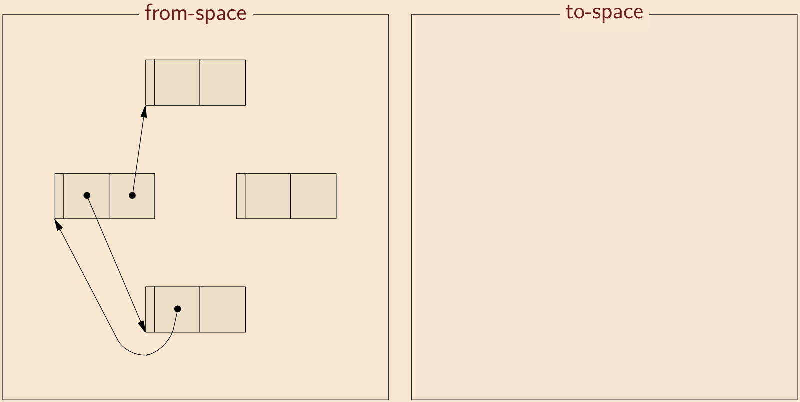
Copying collection: example

Collect

copy live blocks to to-space (starting at the root)

leave **forwarding addresses** in from-space

switch roles of spaces



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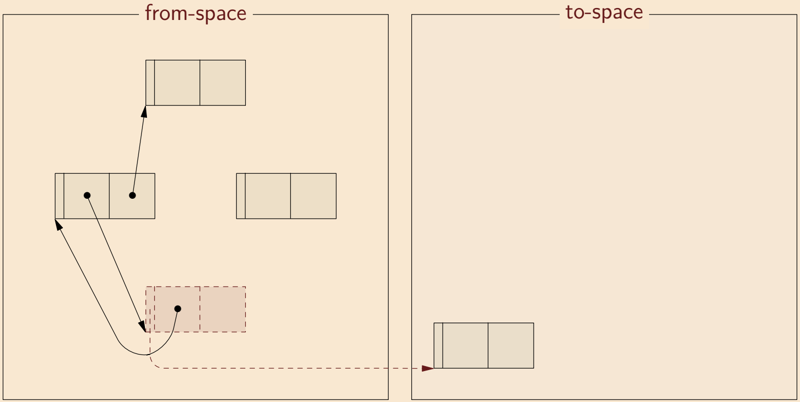

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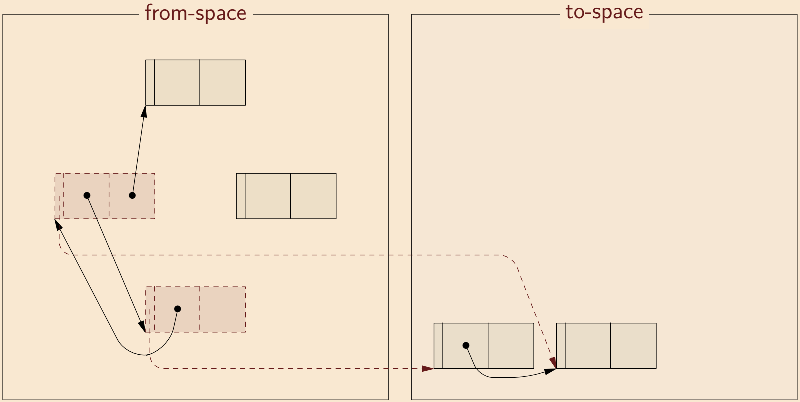

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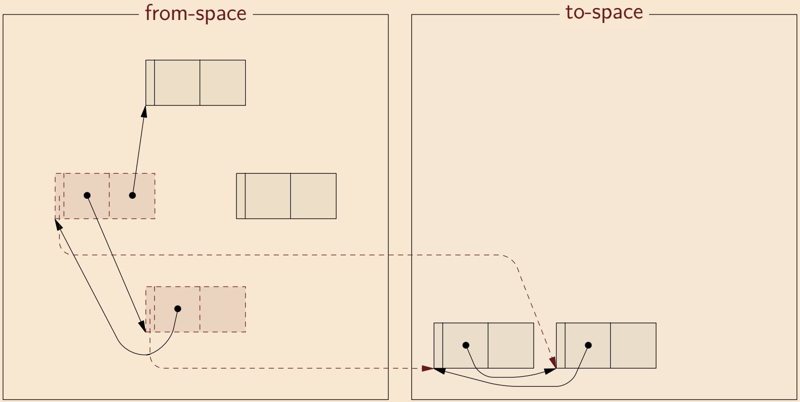

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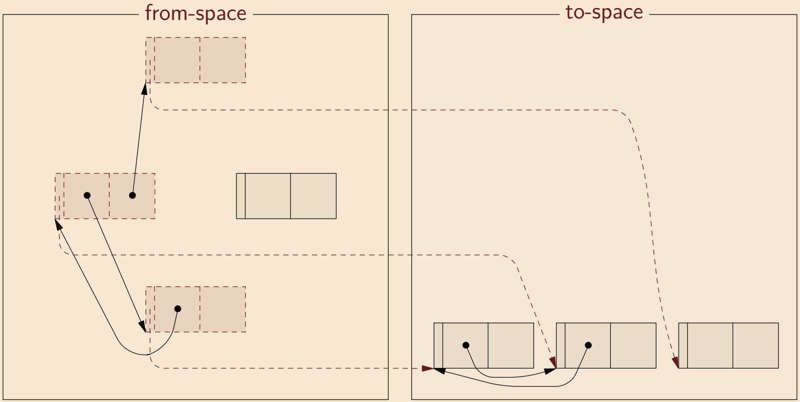

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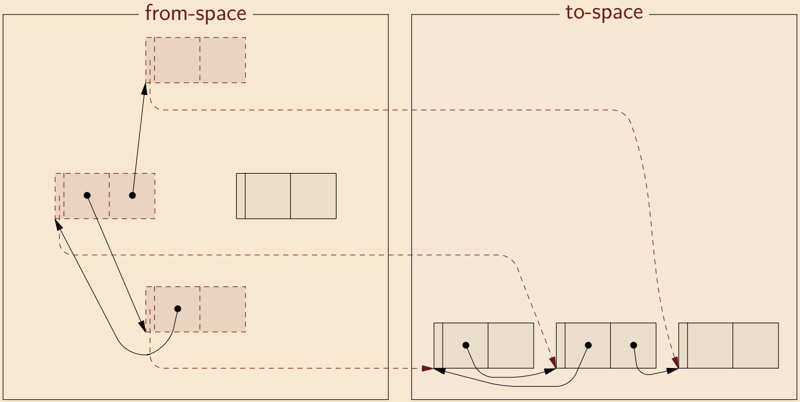

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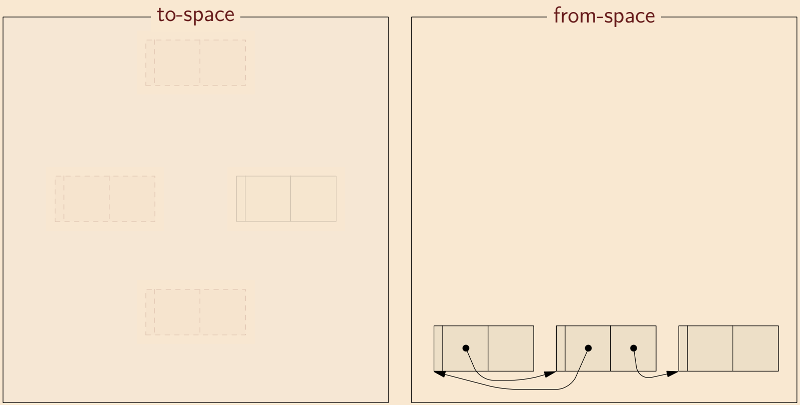


Copying collection: advantages and drawbacks

Advantages of copying garbage collection:

- \+ Reasonably simple
- \+ Collects cycles
- \+ Has **running time propotional to the number of live objects**
- \+ **Automatically compacts** memory, eliminating fragmentation
- \+ Very low allocation costs (pointer bump)

Drawbacks of copying garbage collection

- – Uses **twice as much memory** as the program requires

Generational garbage collection

Generational GC: motivation

Observation: scanning all live objects takes a long time

Observation: programs often allocate a lot (hundreds of MB per second)

Observation: object lifetimes are mostly very short or relatively long

Example **evidence** (much more is available):

$> 98\%$ of collected garbage had been allocated and discarded since previous collection

(Foderaro and Fateman, 1981)

$80 - 98\%$ of objects die before 1MB old

(Wilson, 1994)

$50 - 90\%$ of Common Lisp objects die before 10KB old

(Zorn, 1989)

Generational GC: idea

Key idea: focus on young objects

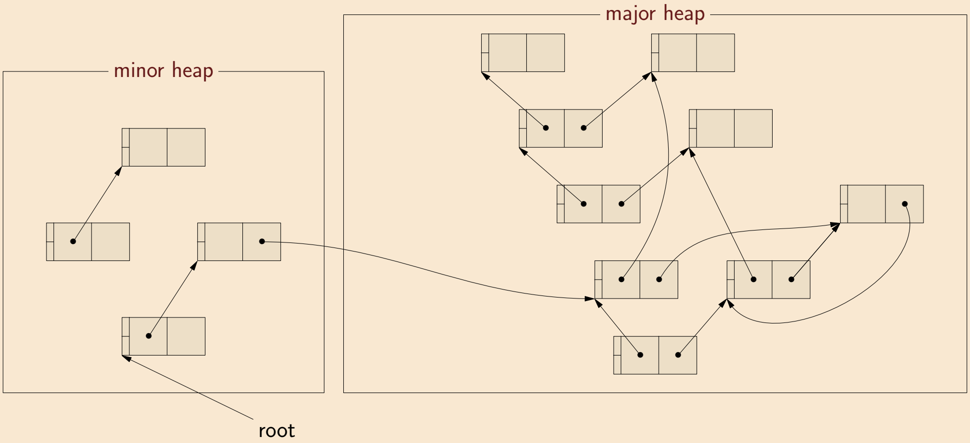
Mechanism:

- divide heap into $2+$ generations
- frequently collect young generations (fast)
- promote surviving objects to old generations
- occasionally collect old generations (slow)

Many **variations** (e.g. generations can use different collection schemes)

Generational GC: example

Copying collector for minor heap / mark-and-sweep for major heap



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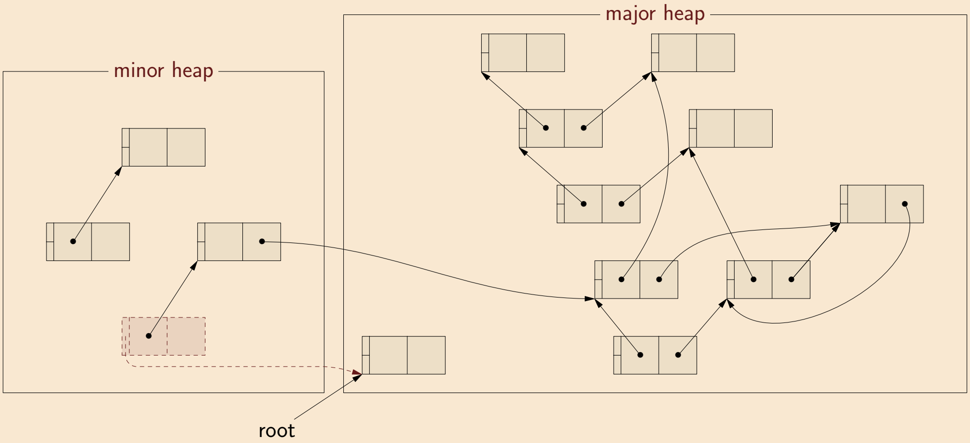

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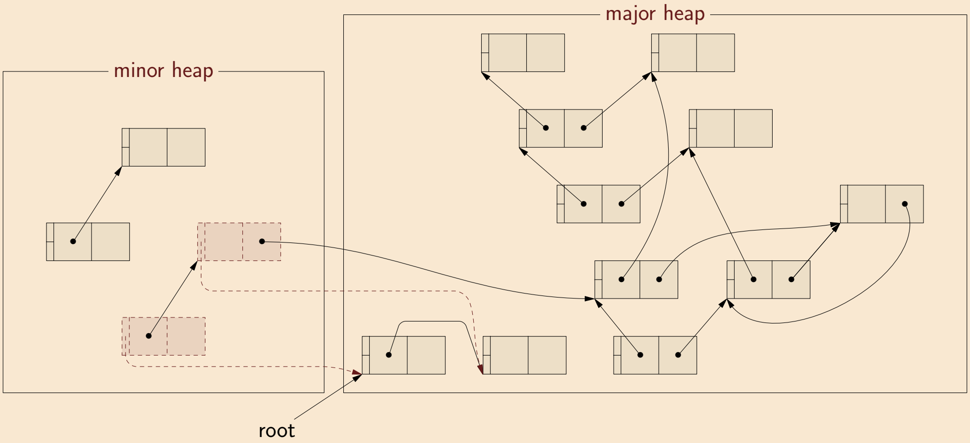

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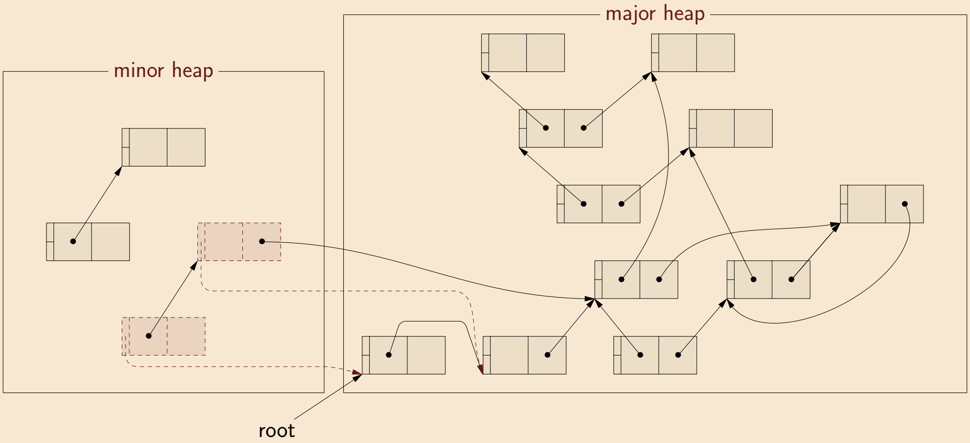

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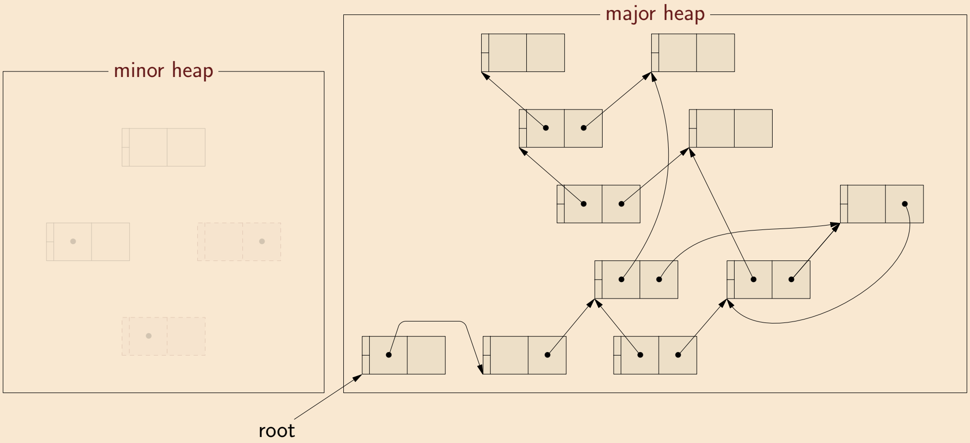

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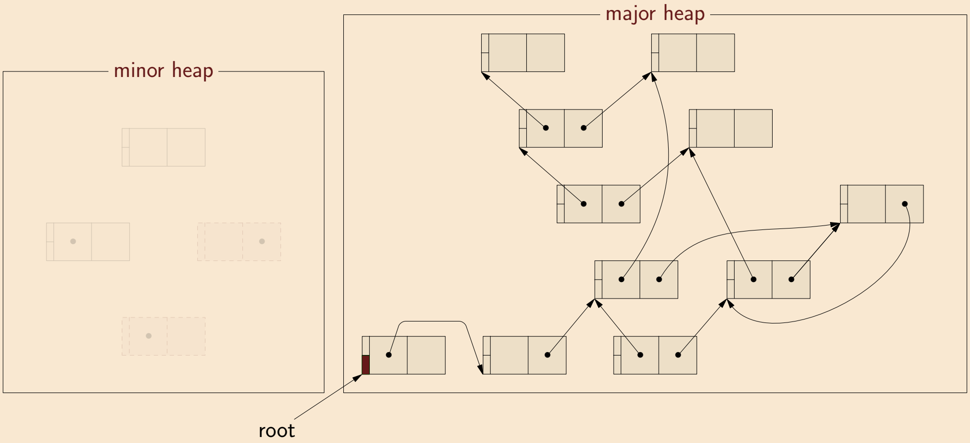

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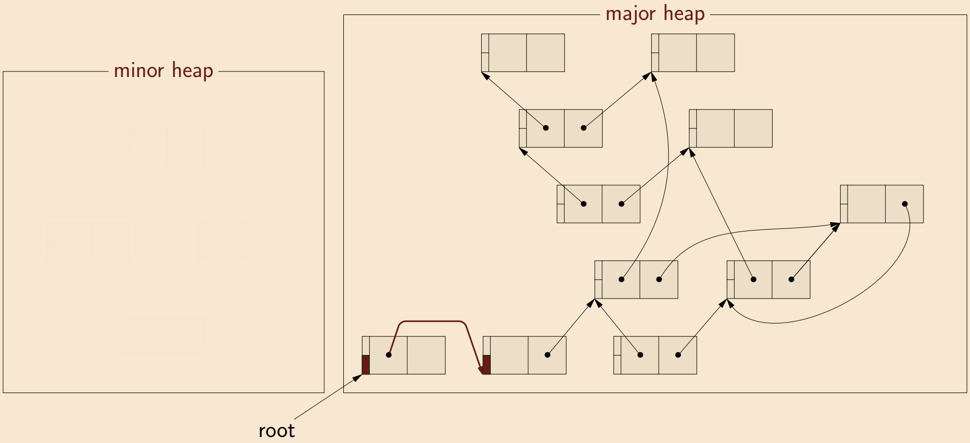

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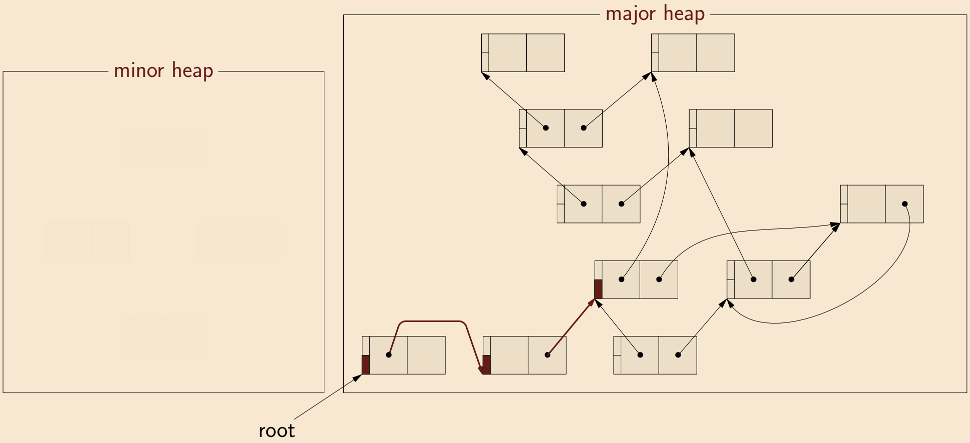

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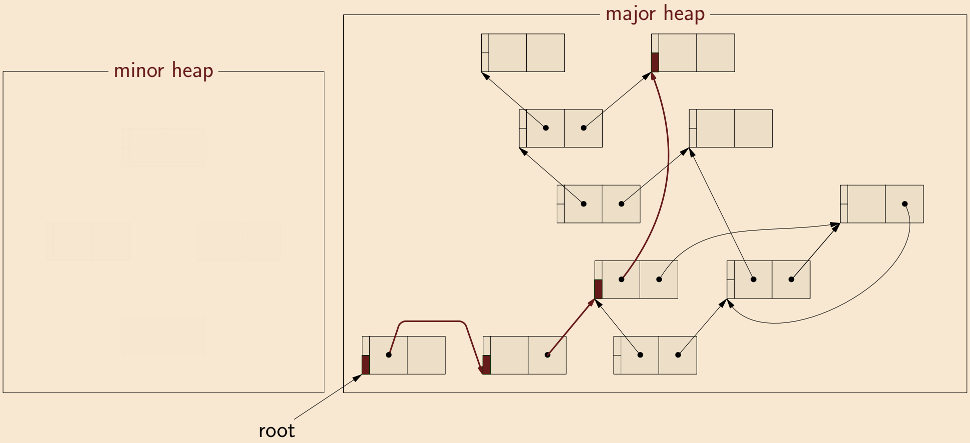

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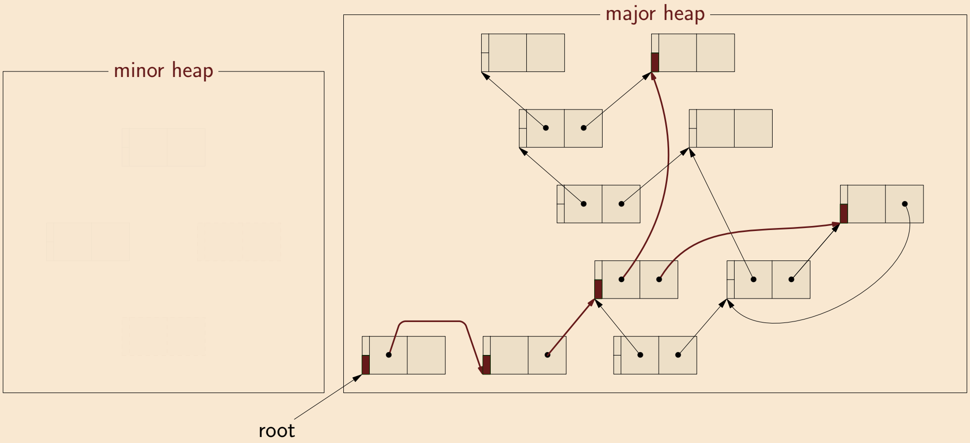
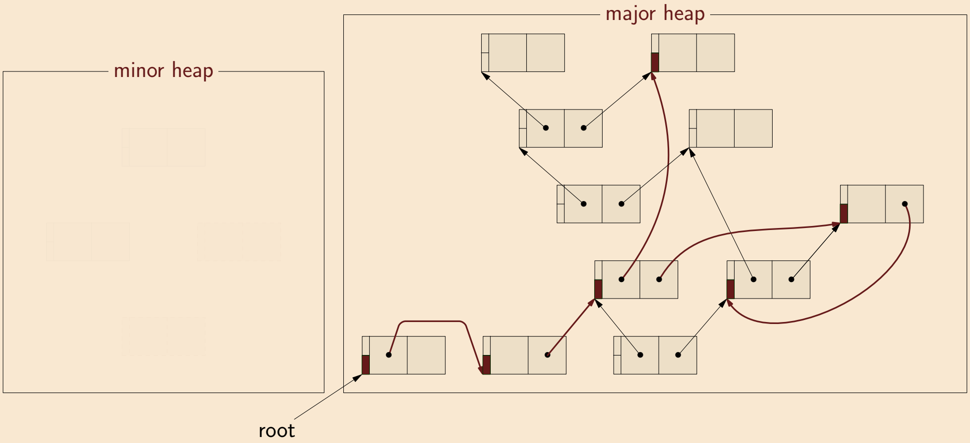


Memory
Reference counting
Mark & sweep
Copying
Generations

Copying collector for minor heap / mark-and-sweep for major heap



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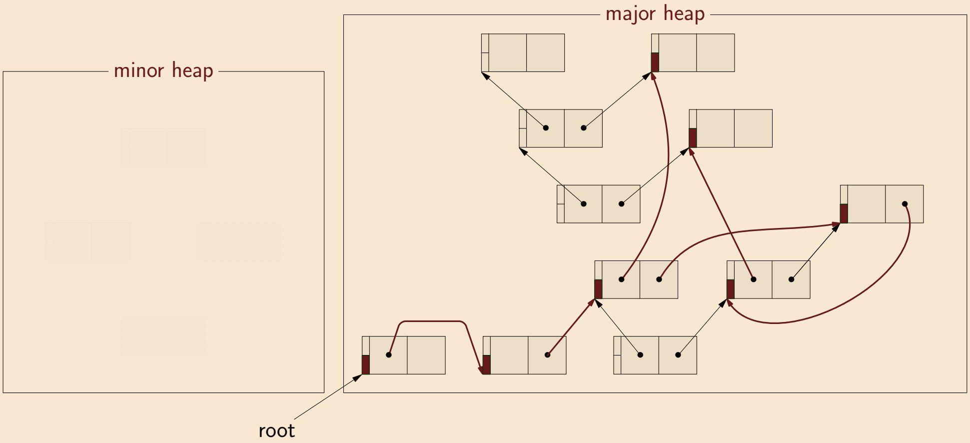

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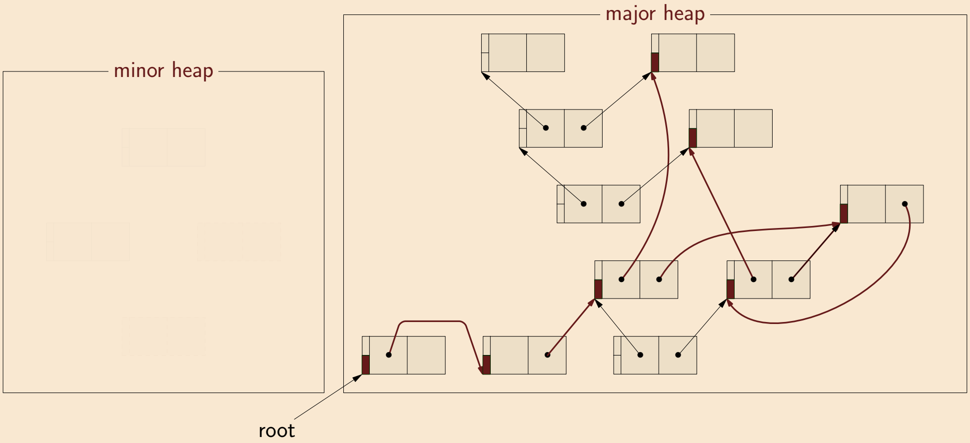

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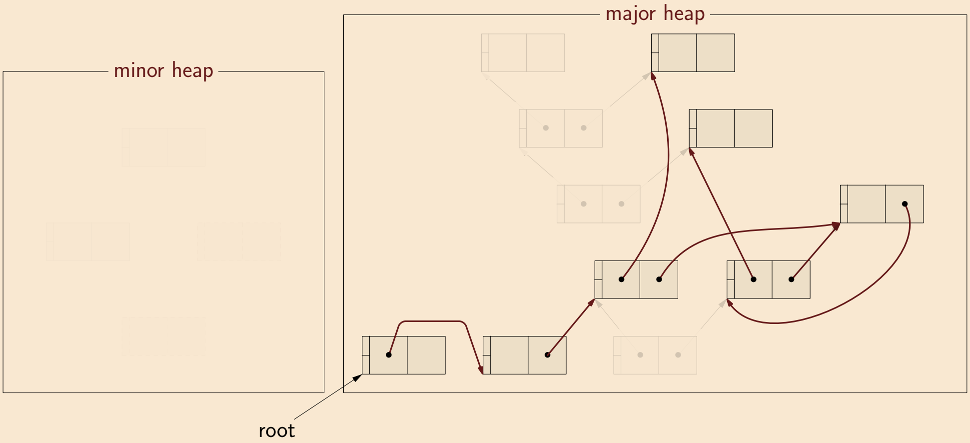

Generational GC: advantages & complexities

Advantages of generational garbage collection:

+ reduce pauses (to $100\mu s$ or less; suitable for interactive programs)
+ avoid wasted time scanning long-lived objects

Complexities of generational garbage collection:

- must distinguish between old & young pointers
- hard to find generation roots (consider pointers from old to young objects)
- can use > 2 generations, all with different policies

Next time: exceptions