第9章 虚拟内存

Dynamic Memory Allocation: Advanced Concepts
动态存储分配:高级概念

100076202： 计算机系统导论

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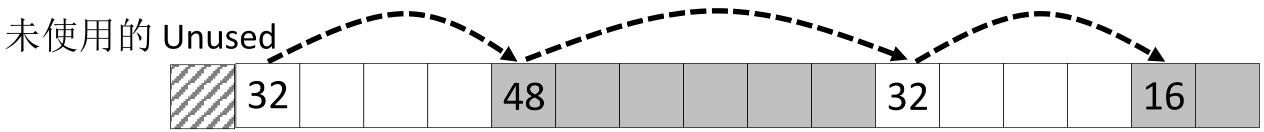
议题 Today

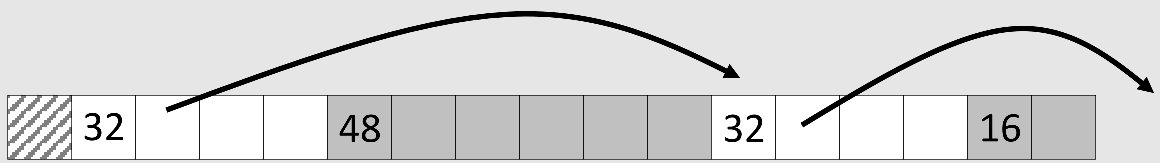
- **显式空闲链表 Explicit free lists**
- 分离的空闲链表 Segregated free lists
- 垃圾收集 Garbage collection
- 内存相关的风险和陷阱 Memory-related perils and pitfalls

跟踪空闲块 Keeping Track of Free Blocks

- 方法1：隐式空闲链表使用长度链接所有块 **Method 1: *Implicit free list* using length—links all blocks**



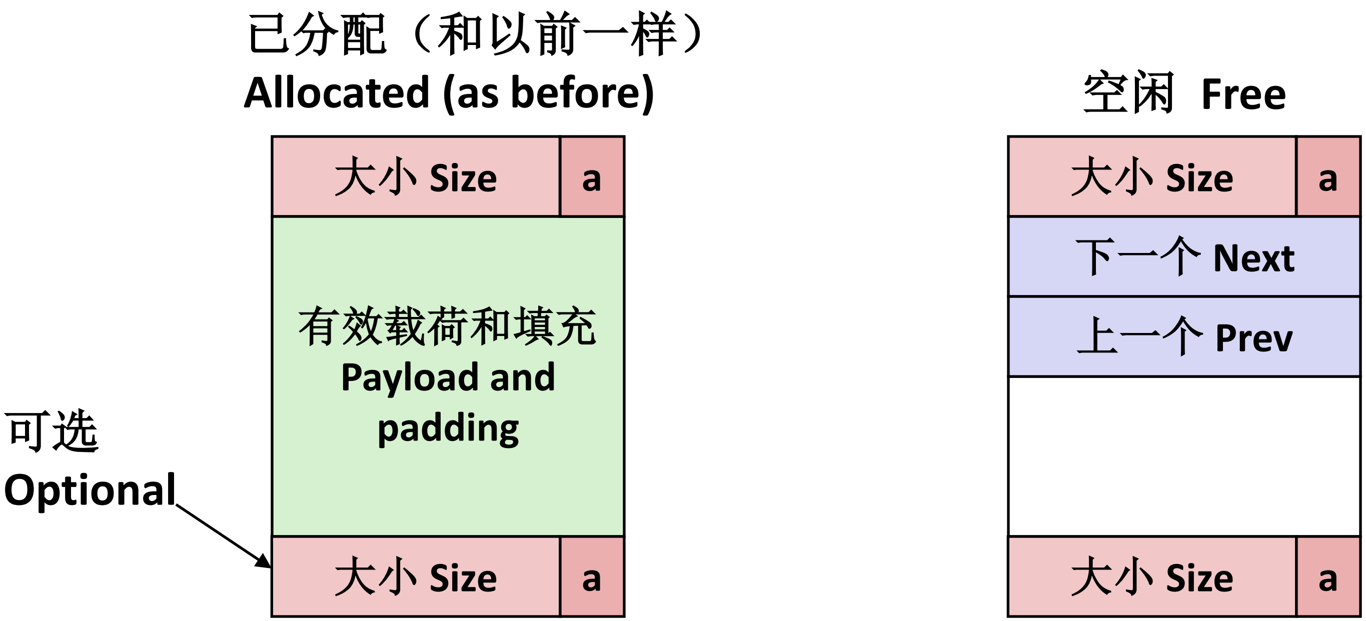
- 方法2：显式空闲链表使用指针串接空闲块 **Method 2: *Explicit free list* among the free blocks using pointers**



- 方法3：分离的空闲链表 **Method 3: *Segregated free list***
  - 不同大小的块使用不同的链表管理 Different free lists for different size classes

- 方法4：根据大小排序块 **Method 4: *Blocks sorted by size***
  - 使用平衡红黑树，每个空闲块内包含指针和用作键值的长度 Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

显式空闲链表 Explicit Free Lists

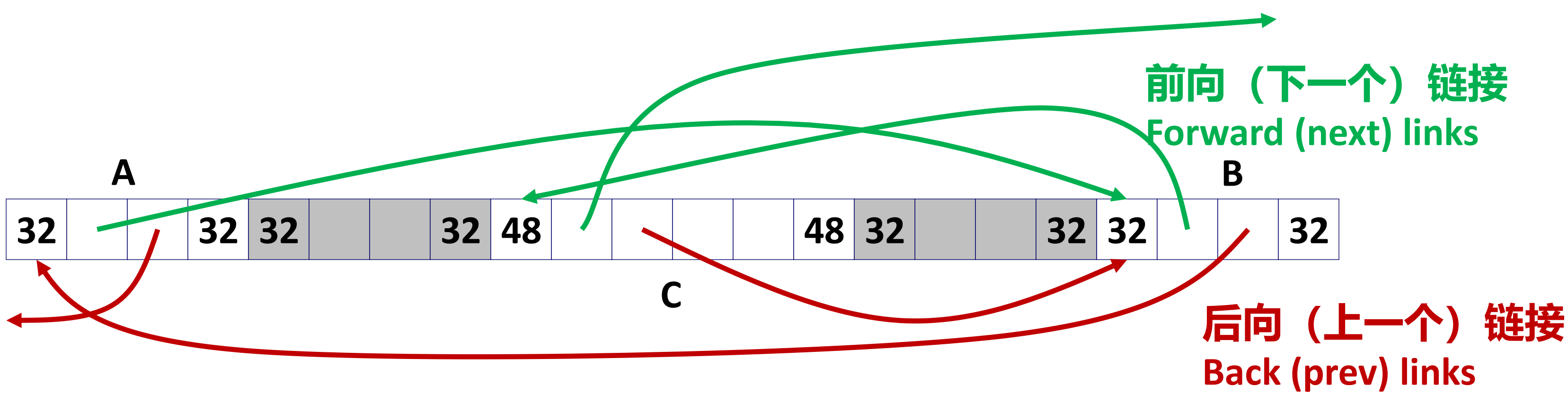


- 维护空闲块链表，而不是所有块 **Maintain list(s) of *free* blocks, not *all* blocks**
  - 下一个空闲块可能在任一地方 The “next” free block could be anywhere
    - 所以需要存储前向/后向指针，不只是大小 So we need to store forward/back pointers, not just sizes
  - 仍然需要使用边界标记进行合并 Still need boundary tags for coalescing
    - 根据内存顺序发现邻接块 To find adjacent blocks according to memory order
  - 幸运的是我们只需要跟踪空闲块，所以可以使用有效载荷区域 Luckily we track only free blocks, so we can use payload area

显式空闲链表 Explicit Free Lists

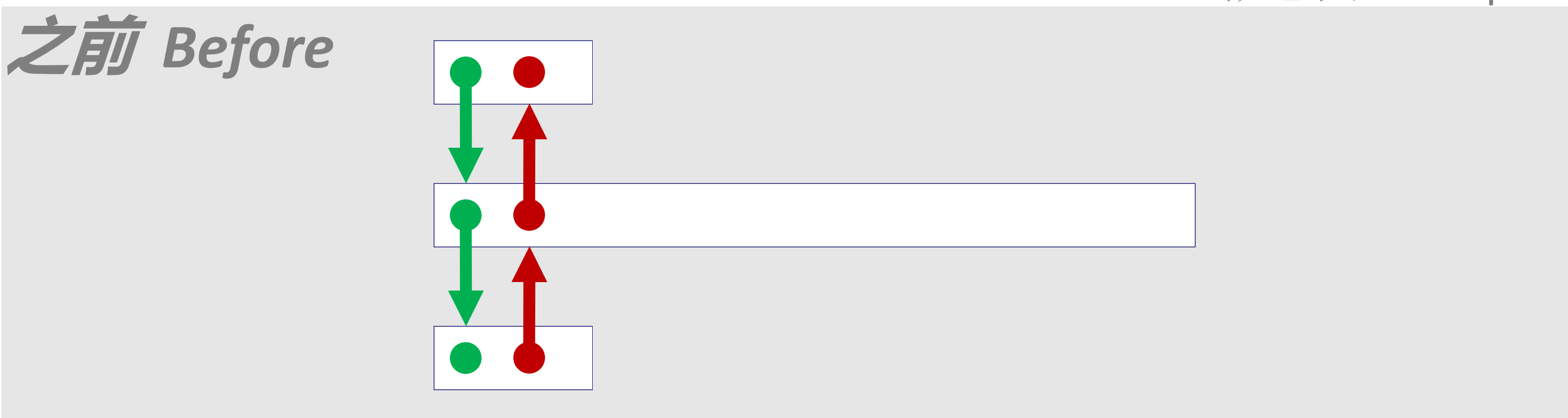
- 逻辑上 Logically:

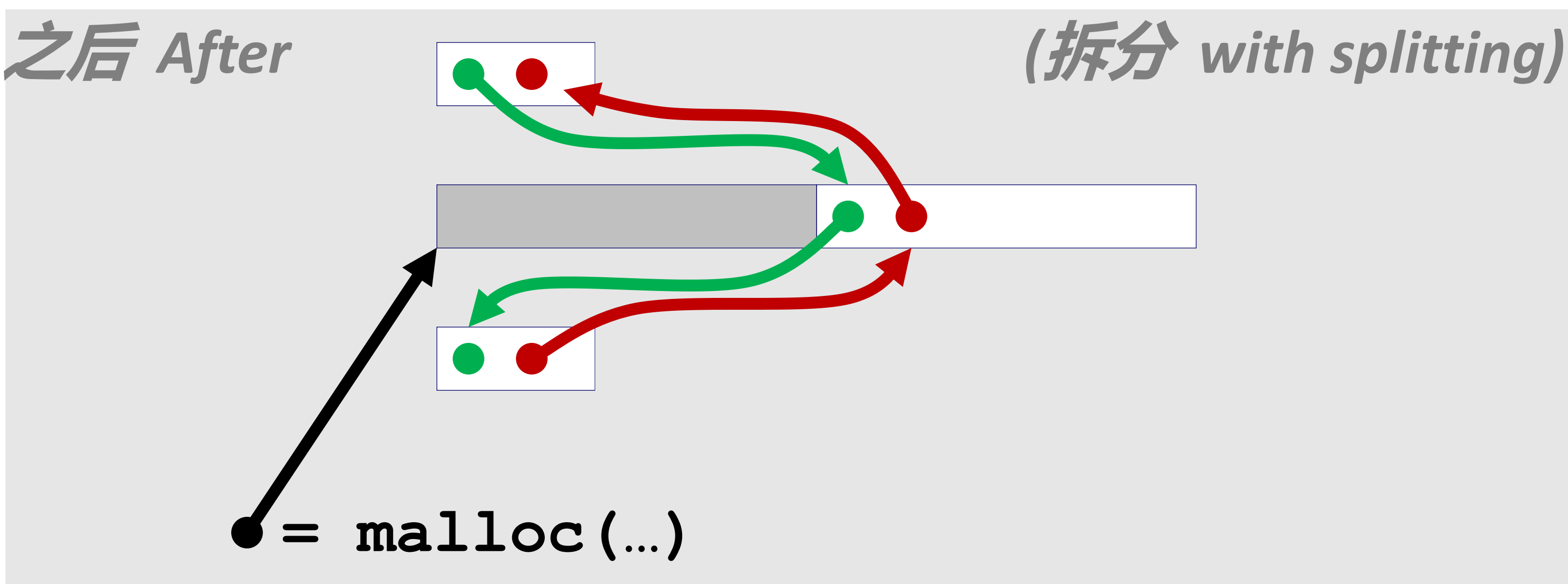
- 物理上：块可能是任意顺序 Physically: blocks can be in any order



从显式空闲链表分配
Allocating From Explicit Free Lists

概念图 conceptual graphic





释放空闲块到显式空闲链表
Freeing With Explicit Free Lists

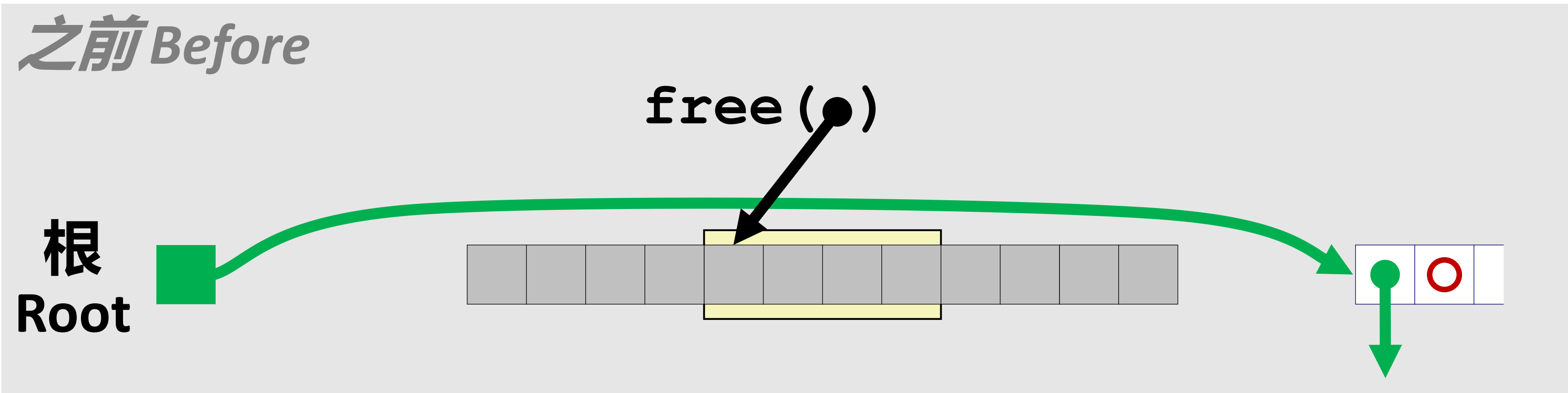
- ***插入策略：*** 在空闲链表的什么位置插入一个新的空闲块？ ***Insertion policy*: Where in the free list do you put a newly freed block?**
- 后进先出策略 **LIFO (last-in-first-out) policy**
  - 在空闲链表的开始插入空闲块 Insert freed block at the beginning of the free list
  - ***优点：*** 简单并且常数时间完成 ***Pro:*** simple and constant time
  - ***缺点：*** 研究表明比地址排序导致更多的碎片 ***Con:*** studies suggest fragmentation is worse than address ordered

- 地址排序策略 **Address-ordered policy**
  - 插入空闲块以便空闲链表块始终按地址排序 Insert freed blocks so that free list blocks are always in address order:

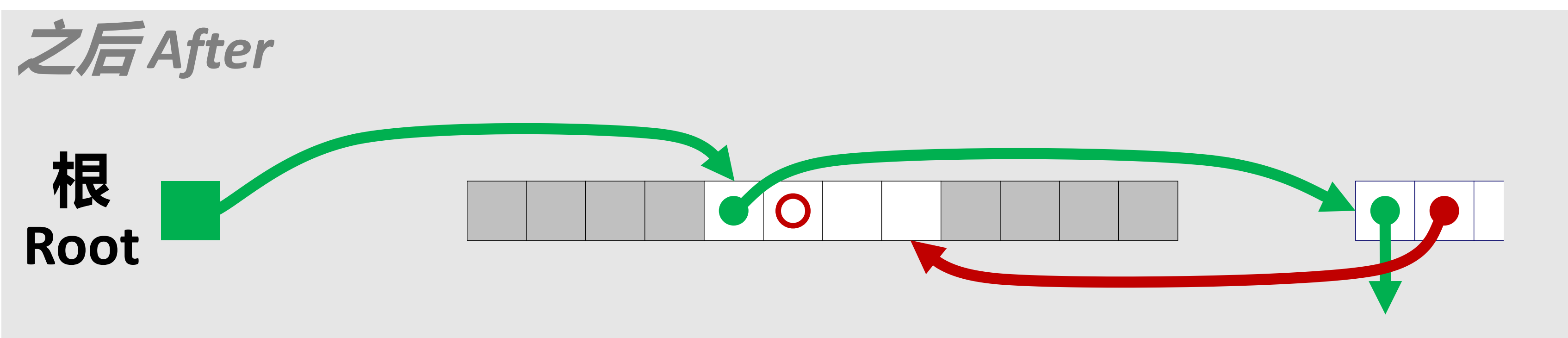
    addr(prev) < addr(curr) < addr(next)
  - ***缺点：*** 需要搜索 ***Con:*** requires search
  - ***优点：*** 研究表明比LIFO有低的内存碎片 ***Pro:*** studies suggest fragmentation is lower than LIFO

基于LIFO策略的释放（案例1）
Freeing With a LIFO Policy (Case 1)

已分配 Allocated		已分配 Allocated	概念图 conceptual graphic

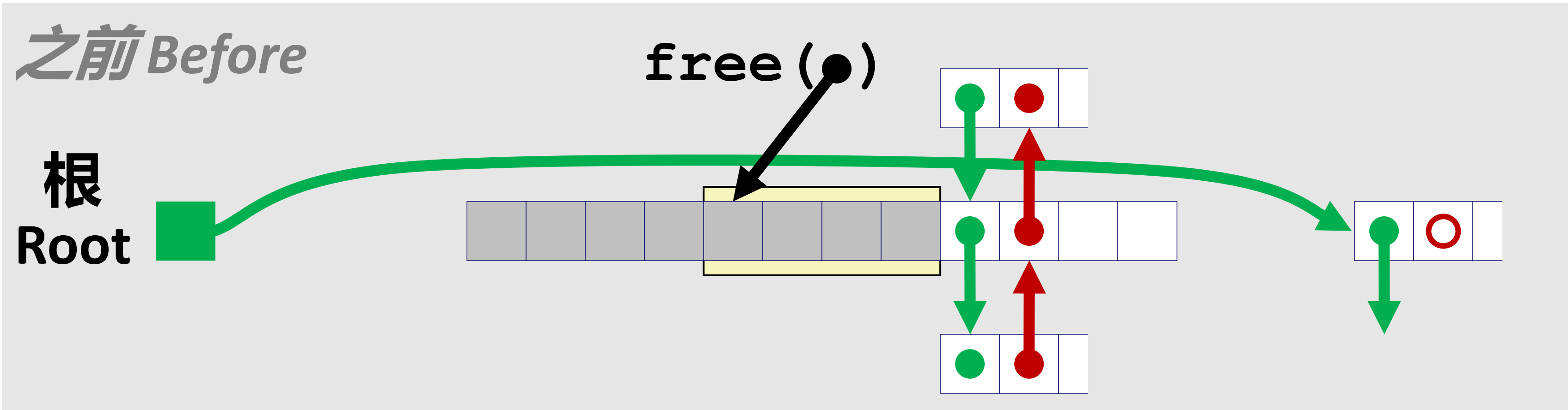


- 将空闲块插入到链表头 Insert the freed block at the root of the list

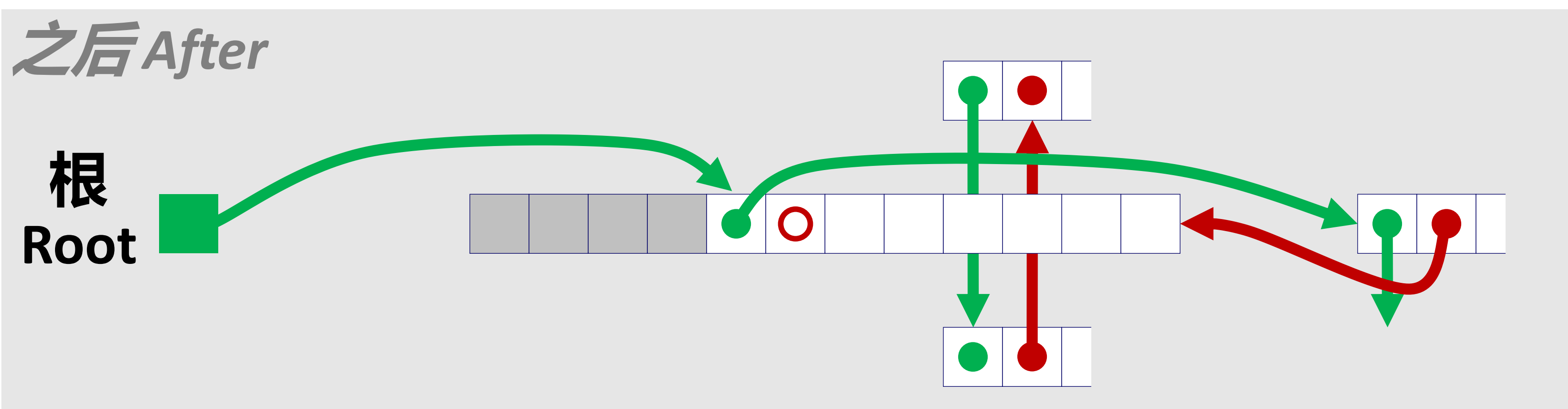


基于LIFO策略的释放（案例2）
Freeing With a LIFO Policy (Case 2)

已分配 Allocated | 空闲 Free　　概念图 conceptual graphic



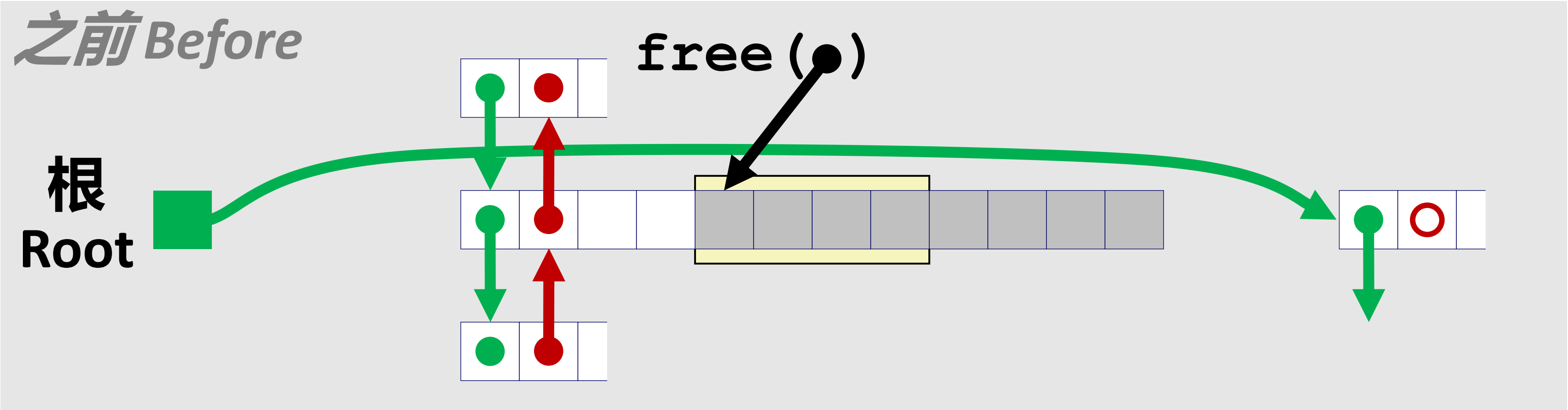
- 拼接出后续块，合并两个块并在链表头插入新块 **Splice out successor block, coalesce both memory blocks and insert the new block at the root of the list**



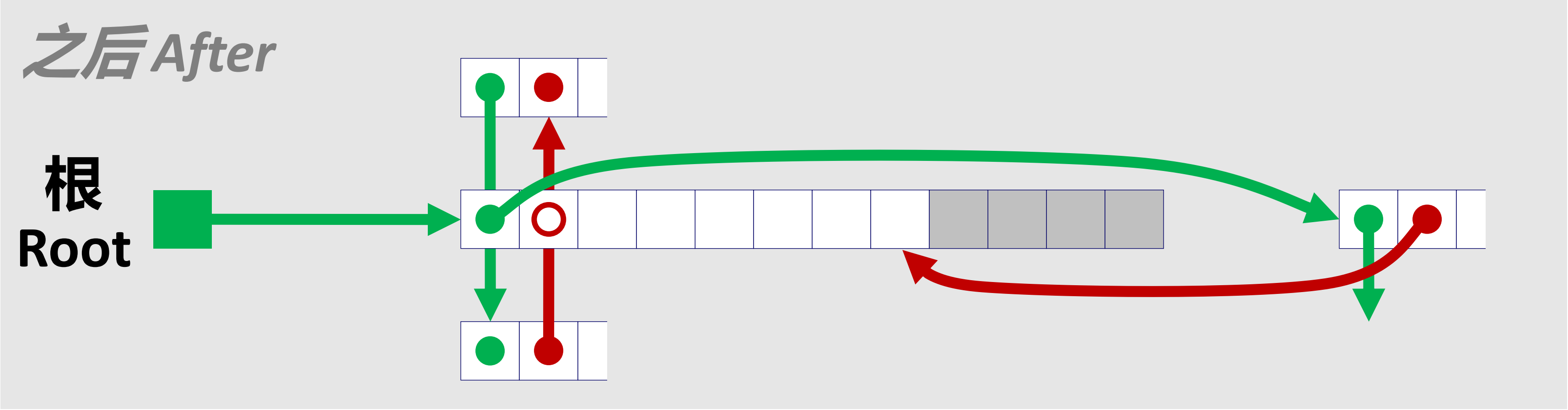
基于LIFO策略的释放（案例3）
Freeing With a LIFO Policy (Case 3)

空闲 Free		已分配Allocated

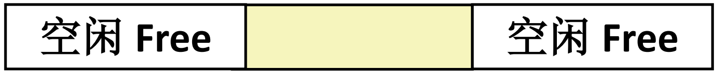
概念图 conceptual graphic



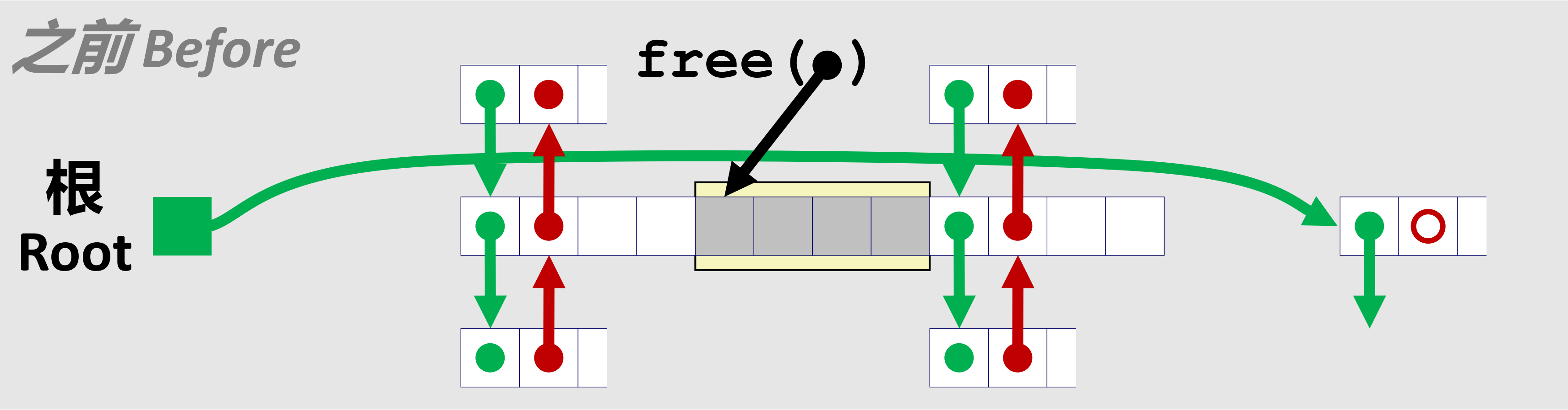
- 拼接出前驱块，合并两个块并在链表头插入新块 Splice out predecessor block, coalesce both memory blocks, and insert the new block at the root of the list



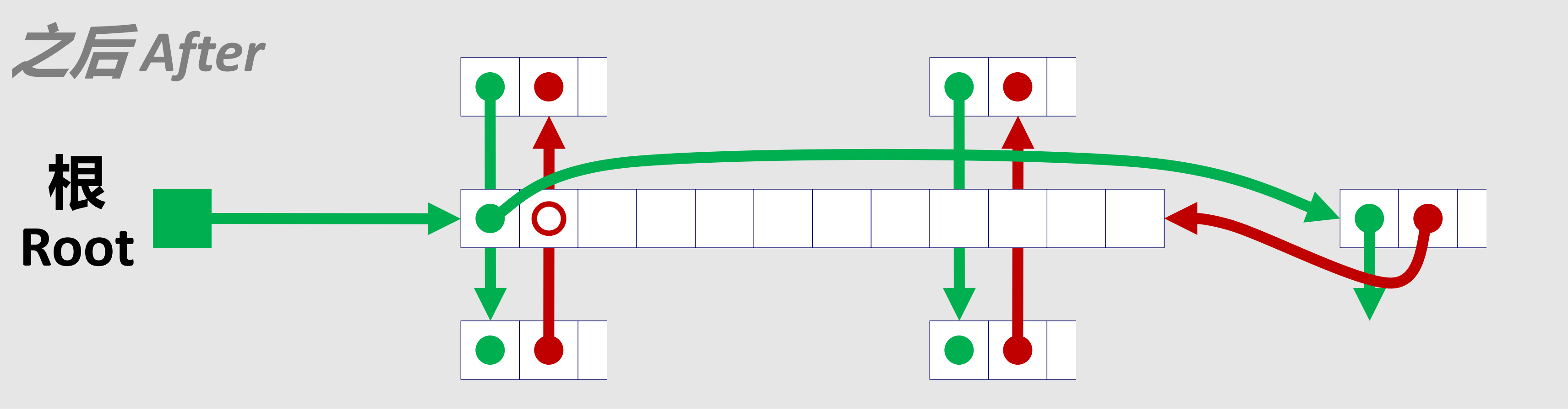
基于LIFO策略的释放（案例4）
Freeing With a LIFO Policy (Case 4)



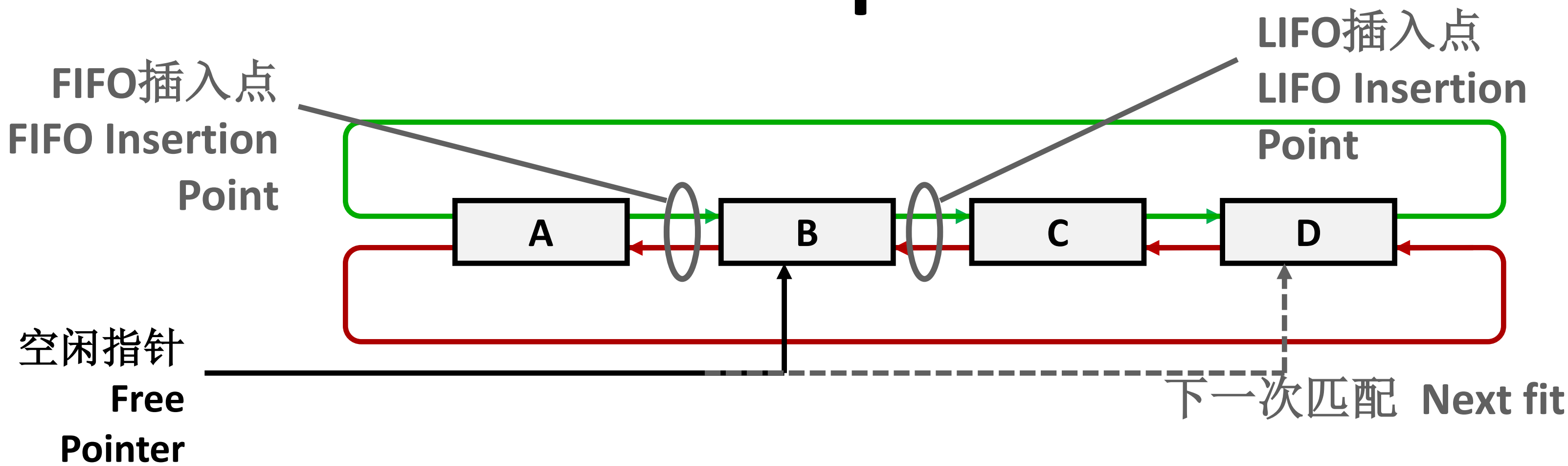
概念图 conceptual graphic



- 拼接出前驱和后继块，合并三个块并在链表头插入新块 **Splice out predecessor and successor blocks, coalesce all 3 memory blocks and insert the new block at the root of the list**



一些建议：实现技巧
Some Advice: An Implementation Trick



- 使用循环双向链表 **Use circular, doubly-linked list**
- 用单一数据结构支持多种方法 **Support multiple approaches with single data structure**
- 首次匹配对下一次匹配 **First-fit vs. next-fit**
  - 要么保持空闲指针固定，要么随搜索列表移动 Either keep free pointer fixed or move as search list
- 后进先出对先进先出 **LIFO vs. FIFO**
  - 插入做为下一个块（LIFO）或做为上一个块 Insert as next block (LIFO), or previous block (FIFO)

显式链表总结 Explicit List Summary

- **与隐式链表相比 Comparison to implicit list:**
  - 分配时间与空闲块的数量成线性时间，而不是所有的块 Allocate is linear time in number of ***free*** blocks instead of ***all*** blocks
    - 当内存大部分被占用的时候快很多 ***Much faster*** when most of the memory is full
  - 由于需要从链表中删除和向链表中插入块，分配和释放稍微复杂一些 Slightly more complicated allocate and free since needs to splice blocks in and out of the list
  - 链接需要一些额外的空间（每个块需要2个额外的字） Some extra space for the links (2 extra words needed for each block)
    - 会增加内部碎片吗？ Does this increase internal fragmentation?
- **链表通常是和分离的空闲链表一起使用的 Most common use of linked lists is in conjunction with segregated free lists**
  - 保持多个不同大小类的链表，或者为不同类型的对象设置不同的链表 Keep multiple linked lists of different size classes, or possibly for different types of objects

议题 Today

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- **分离的空闲链表 Segregated free lists**
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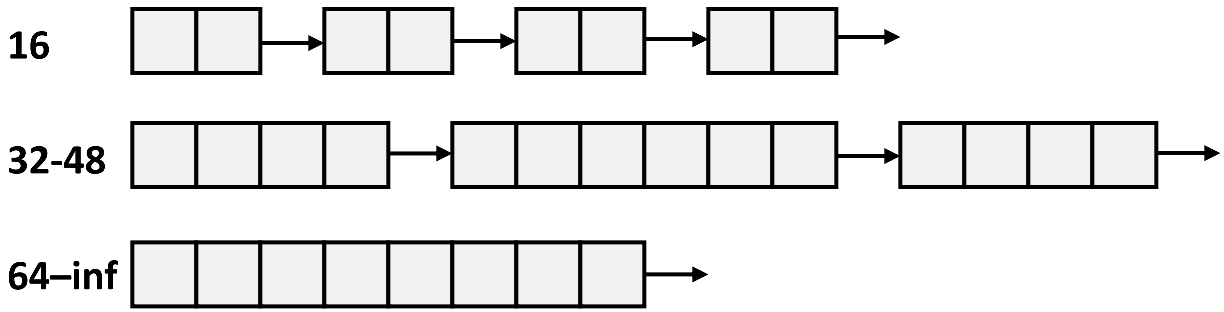
- 内存相关的风险和陷阱 Memory-related perils and pitfalls

分离空闲链表（Seglist）分配器
Segregated List (Seglist) Allocators

- 每个不同大小类块有自己的空闲链表 **Each *size class* of blocks has its own free list**



- 通常比较小的块有自己单独的类 **Often have separate classes for each small size**
- 对于比较大的块：每个2的指数区间有一个类 **For larger sizes: One class for each size** $[2^i+1, 2^{i+1}]$

分离空闲链表分配器 Seglist Allocator

- 空闲链表数组中的每个元素对应某个大小类 **Given an array of free lists, each one for some size class**

- 分配大小为n的块时： **To allocate a block of size *n*:**
  - 搜索对应的空闲链表，其中的块大小m> n Search appropriate free list for block of size *m* > *n*
  - 如果找到一个合适的块： If an appropriate block is found:
    - 拆分块并将碎片挂接到对应的链表（可选） Split block and place fragment on appropriate list (optional)
  - 如果没找到，则尝试下一个更大的链表 If no block is found, try next larger class
  - 重复以上步骤直到找到一个块 Repeat until block is found

- 如果没找到： **If no block is found:**
  - 从OS申请更多的堆内存（使用sbrk()） Request additional heap memory from OS (using `sbrk()`)
  - 从新申请的内存分配大小为n字节的块 Allocate block of *n* bytes from this new memory
  - 将剩下的当做一个空闲块放到最大的类表中 Place remainder as a single free block in largest size class.

Seglist分配器(续) Seglist Allocator (cont.)

- **释放一个块： To free a block:**
  - 合并并放到合适的链表中 Coalesce and place on appropriate list

- **seglist分配器相对非seglist分配器的优点（均采用首次匹配） Advantages of seglist allocators vs. non-seglist allocators (both with first-fit)**
  - 高吞吐率 Higher throughput
    - 对于2的指数次方的大小类是log时间复杂度 log time for power-of-two size classes
  - 更好的内存利用率 Better memory utilization
    - 分离空闲链表中的首次匹配搜索近似于整个堆上的最佳匹配搜索 First-fit search of segregated free list approximates a best-fit search of entire heap.
    - 极端案例：如果每个块有自己的大小类，则等价于最佳匹配 Extreme case: Giving each block its own size class is equivalent to best-fit.

内存分配器的更多资料 More Info on Allocators

- **“计算机编程的艺术” D. Knuth, “*The Art of Computer Programming*”, vol 1, 3rd edition, Addison Wesley, 1997**
  - 关于动态内存分配的经典参考 The classic reference on dynamic storage allocation

- **“动态存储分配：调查与评论” Wilson et al, “*Dynamic Storage Allocation: A Survey and Critical Review*”, Proc. 1995 Int’l Workshop on Memory Management, Kinross, Scotland, Sept, 1995.**
  - 综合调查 Comprehensive survey
  - 访问CS:APP学生网站 Available from CS:APP student site (csapp.cs.cmu.edu)

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隐式内存管理：垃圾收集
Implicit Memory Management: Garbage Collection

- *垃圾收集*：自动回收堆中分配的内存块-应用程序不用负责释放 ***Garbage collection:*** **automatic reclamation of heap-allocated storage—application never has to free**

```
void foo() {
   int *p = malloc(128);
   return; /* p block is now garbage */
}
```

- **许多动态语言的共同特性 Common in many dynamic languages:**
  - Python, Ruby, Java, Perl, ML, Lisp, Mathematica

- **C和C++存在变种（保守的垃圾收集） Variants ("conservative" garbage collectors) exist for C and C++**
  - 然而，不一定收集所有垃圾 However, cannot necessarily collect all garbage

垃圾收集 Garbage Collection

- 内存管理器如何知道内存什么时候可以被释放？ **How does the memory manager know when memory can be freed?**
  - 通常我们是不知道将来会用到哪些，因为程序执行是有路径分支的 In general we cannot know what is going to be used in the future since it depends on conditionals
  - 但是如果某些块没有指针指向则可以确定是不会用的 But we can tell that certain blocks cannot be used if there are no pointers to them

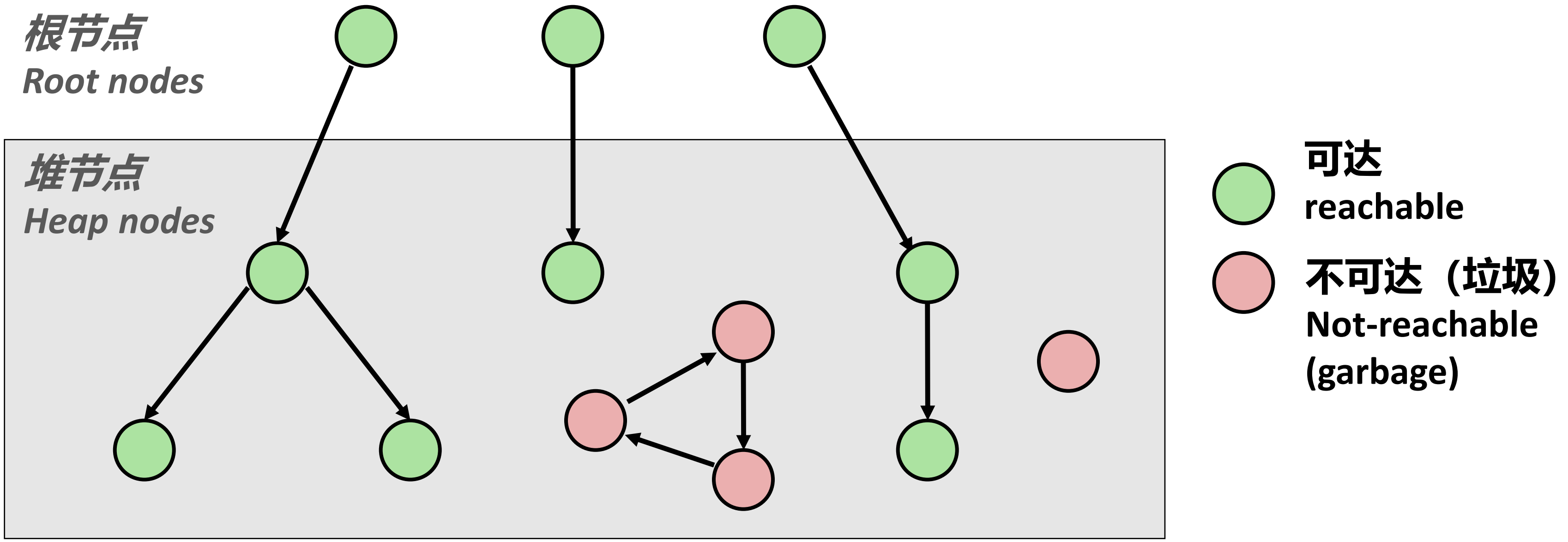
- 关于指针的一些假设 **Must make certain assumptions about pointers**
  - 内存管理器能够区分指针和非指针 Memory manager can distinguish pointers from non-pointers
  - 所有的指针指向块的开始地址 All pointers point to the start of a block
  - 不能隐藏指针 Cannot hide pointers
    (例如，强制转为int，再转回来 e.g., by coercing them to an `int`, and then back again)

经典垃圾收集算法 Classical GC Algorithms

- 标记清除收集算法 **Mark-and-sweep collection (McCarthy, 1960)**
  - 不需要移动内存块（除非需要平移压紧占用部分） Does not move blocks (unless you also “compact”)
- 引用计数算法 **Reference counting (Collins, 1960)**
  - 不需要移动内存块（不讨论） Does not move blocks (not discussed)
- 拷贝收集算法 **Copying collection**（不讨论） **(Minsky, 1963)**
  - 需要移动内存块 Moves blocks (not discussed)
- 按代垃圾收集算法 **Generational Collectors (Lieberman and Hewitt, 1983)**
  - 基于生命周期的收集 Collection based on lifetimes
    - 大部分内存块很快变为垃圾 Most allocations become garbage very soon
    - 主要聚焦在最近分配的区域内开展回收工作 So focus reclamation work on zones of memory recently allocated
- 更详细信息参见：“垃圾收集：自动动态内存算法” **For more information:**
  Jones and Lin, “*Garbage Collection: Algorithms for Automatic Dynamic Memory*”, John Wiley & Sons, 1996.

将内存当做一个图 Memory as a Graph

- 我们将内存看做一个有向图 **We view memory as a directed graph**
  - 每个块是图中的一个节点 Each block is a node in the graph
  - 每个指针是图中的一条边 Each pointer is an edge in the graph
  - 不在堆中但是持有指向堆中指针的位置称为根节点（例如，寄存器，栈中元素，以及全局变量） Locations not in the heap that contain pointers into the heap are called ***root*** nodes (e.g. registers, locations on the stack, global variables)

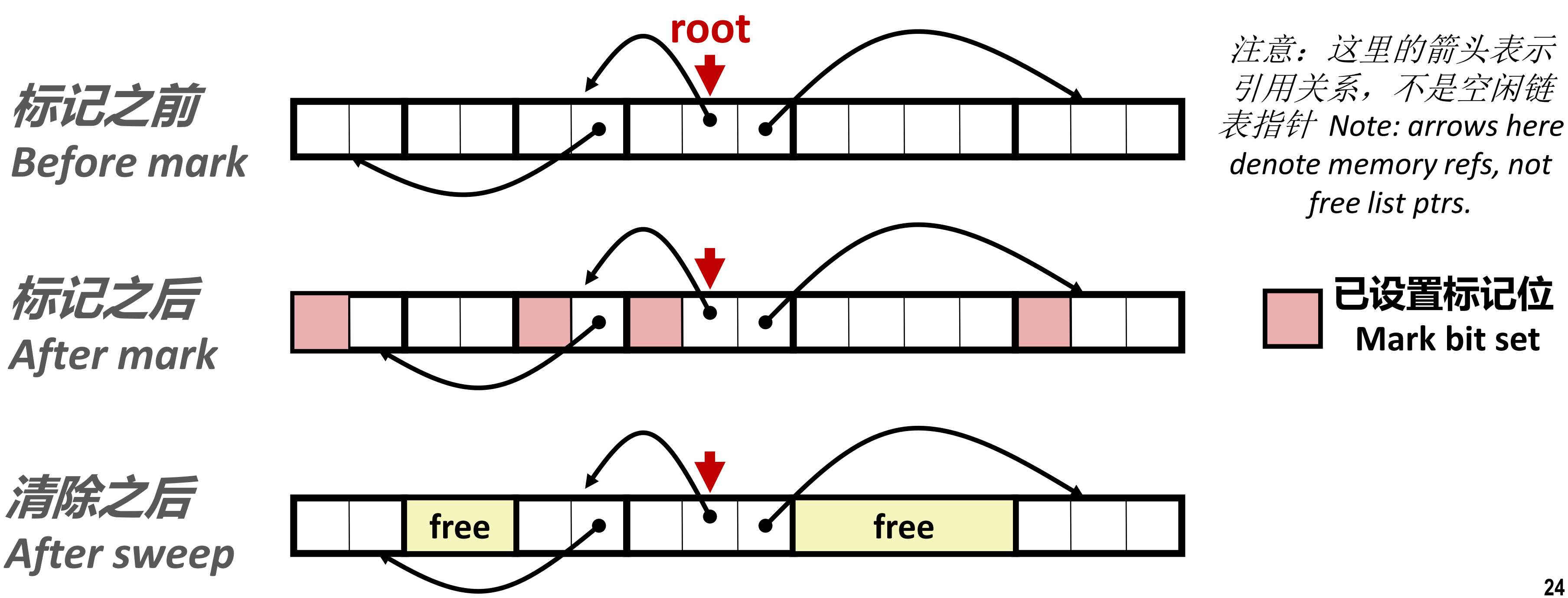


如果有从根节点到某个节点的路径则这个节点是可达的 A node (block) is *reachable* if there is a path from any root to that node.

不可达的都是垃圾（应用程序不再需要） Non-reachable nodes are *garbage* (cannot be needed by the application)

标记清除收集算法 Mark and Sweep Collecting

- 可以基于malloc/free包构建 **Can build on top of malloc/free package**
  - 一直使用malloc直到空间不够用 Allocate using `malloc` until you "run out of space"
- 当内存不够用 **When out of space:**
  - 在每个块的头部使用额外的标记位 Use extra ***mark bit*** in the head of each block
  - ***Mark:*** 从根节点开始并对所有可达节点设置标记位 Start at roots and set mark bit on each reachable block
  - ***Sweep:*** 扫描所有的块并释放未标记的块 Scan all blocks and free blocks that are not marked

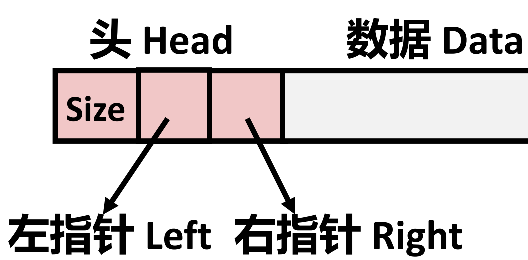


C语言中保守的标记-清除算法
Conservative Mark & Sweep in C

- C程序的一个保守垃圾收集器 **A “conservative garbage collector” for C programs**
  - `is_ptr()` 用来判断一个字是否是指向一个已经分配的内存块的指针 **`is_ptr()`** determines if a word is a pointer by checking if it points to an allocated block of memory
  - 但是，C指针可以指向块中间的位置 But, in C pointers can point to the middle of a block

假设中间的指针可以用于到达块的任何地方，但不能到其他块
Assumes ptr in middle can be used to reach anywhere in the block, but no other block

- 所以要如何找到块的开始？ **So how to find the beginning of the block?**
  - 可以使用一个平衡二叉树跟踪所有已经分配的块(key是块开始地址) Can use a balanced binary tree to keep track of all allocated blocks (key is start-of-block)
  - 平衡二叉树的指针可以存在head中(使用两个额外的字) Balanced-tree pointers can be stored in header (use two additional words)



Left: smaller addresses 较小地址
Right: larger addresses 较大地址

一个简单实现的前提假设
Assumptions For a Simple Implementation

- 应用 **Application**
  - **`new(n)`**：返回指向新块的指针，所有的域清除 returns pointer to new block with all locations cleared
  - **`read(b,i)`**：将块b中位置i的内容读到寄存器 read location **`i`** of block **`b`** into register
  - **`write(b,i,v)`**： 将v写入块b中的位置i write **`v`** into location **`i`** of block **`b`**

- 每个块有一个头部字 **Each block will have a header word**
  - 对b可以使用b[-1]寻址 addressed as **`b[-1]`**, for a block **`b`**
  - 在不同的垃圾收集器里面有不同的用途 Used for different purposes in different collectors
- 垃圾收集器使用的操作 **Instructions used by the Garbage Collector**
  - **`is_ptr(p)`**：确定p是否是一个指针 determines whether **`p`** is a pointer
  - **`length(b)`**: 返回b的长度，不包括头部 returns the length of block **`b`**, not including the header
  - **`get_roots()`**: 返回所有块的根 returns all the roots

标记和清除（续） Mark and Sweep (cont.)

通过内存图的深度优先遍历标记 Mark using depth-first traversal of the memory graph

```
ptr mark(ptr p) {
   if (!is_ptr(p)) return;          // do nothing if not pointer
   if (markBitSet(p)) return;       // check if already marked
   setMarkBit(p);                   // set the mark bit
   for (i=0; i < length(p); i++)   // call mark on all words
     mark(p[i]);                    //   in the block
   return;
}
```

清除阶段通过长度找到下一个块 Sweep using lengths to find next

```
ptr sweep(ptr p, ptr end) {
   while (p < end) {
      if markBitSet(p)
         clearMarkBit();
      else if (allocateBitSet(p))
         free(p);
      p += length(p);
}
```

标记和清除伪代码
Mark and Sweep Pseudocode

通过内存图的深度优先遍历标记 Mark using depth-first traversal of the memory graph

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ptr mark(ptr p) {
    if (!is_ptr(p)) return;
    if (markBitSet(p)) return;
    setMarkBit(p);
    for (i=0; i < length(p); i++)
      mark(p[i]);
    return;
}
```

标记和清除伪代码
Mark and Sweep Pseudocode

通过内存图的深度优先遍历标记 Mark using depth-first traversal of the memory graph

```
ptr mark(ptr p) {
   if (!is_ptr(p)) return;          // if not pointer -> do nothing
   if (markBitSet(p)) return;
   setMarkBit(p);
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     mark(p[i]);
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}
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   for (i=0; i < length(p); i++)   // for each word in p's block
     mark(p[i]);
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}
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     mark(p[i]);                    //  make recursive call
   return;
}
```

清除阶段通过长度找到下一个块 Sweep using lengths to find next block

```
ptr sweep(ptr p, ptr end) {
   while (p < end) {                // for entire heap
      if markBitSet(p)
         clearMarkBit();
      else if (allocateBitSet(p))
         free(p);
      p += length(p+1);
}
```

标记和清除伪代码
Mark and Sweep Pseudocode

通过内存图的深度优先遍历标记 **Mark using depth-first traversal of the memory graph**

```
ptr mark(ptr p) {
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   if (markBitSet(p)) return;       // if already marked -> do nothing
   setMarkBit(p);                   // set the mark bit
   for (i=0; i < length(p); i++)    // for each word in p's block
     mark(p[i]);                    //  make recursive call
   return;
}
```

清除阶段通过长度找到下一个块 **Sweep using lengths to find next block**

```
ptr sweep(ptr p, ptr end) {
   while (p < end) {                // for entire heap
      if markBitSet(p)              // did we reach this block?
         clearMarkBit();
      else if (allocateBitSet(p))
         free(p);
      p += length(p+1);
}
```

标记和清除伪代码
Mark and Sweep Pseudocode

通过内存图的深度优先遍历标记 Mark using depth-first traversal of the memory graph

```
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   if (!is_ptr(p)) return;          // if not pointer -> do nothing
   if (markBitSet(p)) return;       // if already marked -> do nothing
   setMarkBit(p);                   // set the mark bit
   for (i=0; i < length(p); i++)   // for each word in p's block
     mark(p[i]);                    //  make recursive call
   return;
}
```

清除阶段通过长度找到下一个块 Sweep using lengths to find next block

```
ptr sweep(ptr p, ptr end) {
   while (p < end) {                // for entire heap
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```

标记和清除伪代码
Mark and Sweep Pseudocode

通过内存图的深度优先遍历标记 Mark using depth-first traversal of the memory graph

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   for (i=0; i < length(p); i++)    // for each word in p’s block
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   return;
}
```

清除阶段通过长度找到下一个块 Sweep using lengths to find next block

```
ptr sweep(ptr p, ptr end) {
   while (p < end) {                // for entire heap
      if markBitSet(p)              // did we reach this block?
         clearMarkBit();            //  yes -> so just clear mark bit
      else if (allocateBitSet(p))   // never reached: is it allocated?
         free(p);
      p += length(p+1);
}
```

标记和清除伪代码
Mark and Sweep Pseudocode

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清除阶段通过长度找到下一个块 Sweep using lengths to find next block

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         free(p);                   //  yes -> its garbage, free it
      p += length(p+1);
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```

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清除阶段通过长度找到下一个块 Sweep using lengths to find next block

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         clearMarkBit();            //  yes -> so just clear mark bit
      else if (allocateBitSet(p))   // never reached: is it allocated?
         free(p);                   //  yes -> its garbage, free it
      p += length(p+1);             // goto next block
}
```

C指针声明：测试一下你自己
C Pointer Declarations: Test Yourself!

`int *p`	p is a pointer to int
`int *p[13]`	p is an array[13] of pointer to int
`int *(p[13])`	p is an array[13] of pointer to int
`int **p`	p is a pointer to a pointer to an int
`int (*p)[13]`	p is a pointer to an array[13] of int
`int *f()`	f is a function returning a pointer to int
`int (*f)()`	f is a pointer to a function returning int
`int (*(*x[3])())[5]`	x is an array[3] of pointers to functions returning pointers to array[5] of ints

Source: K&R Sec 5.12

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`int **p`	p is a pointer to a pointer to an int
`int (*p)[13]`	p is a pointer to an array[13] of int
`int *f()`	f is a function returning a pointer to int
`int (*f)()`	f is a pointer to a function returning int
`int (*(*x[3])())[5]`	x is an array[3] of pointers to functions returning pointers to array[5] of ints
`int (*(*f())[13])()`	f is a function returning ptr to an array[13] of pointers to functions returning int

Source: K&R Sec 5.12

分析：Parsing: int (*(*f())[13])()

`int (*(*f())[13])()`	f
`int (*(*f())[13])()`	f is a function
`int (*(*f())[13])()`	f is a function that returns a ptr
`int (*(*f())[13])()`	f is a function that returns a ptr to an array of 13
`int (*(*f())[13])()`	f is a function that returns a ptr to an array of 13 ptrs
`int (*(*f())[13])()`	f is a function that returns a ptr to an array of 13 ptrs to functions returning an int

议题 Today

- 显示空闲链表 Explicit free lists
- 分离的空闲链表 Segregated free lists
- 垃圾收集 Garbage collection
- **内存相关的风险和陷阱 Memory-related perils and pitfalls**

内存相关的风险和陷阱
Memory-Related Perils and Pitfalls

- 解引（间接引用）问题指针 **Dereferencing bad pointers**
- 使用未初始化内存 **Reading uninitialized memory**
- 覆盖内存 **Overwriting memory**
- 引用不存在的变量 **Referencing nonexistent variables**
- 重复释放内存块 **Freeing blocks multiple times**
- 引用释放的内存 **Referencing freed blocks**
- 释放内存失败 **Failing to free blocks**

解引（间接引用）问题指针
Dereferencing Bad Pointers

- 经典的scanf bug The classic `scanf` bug

```
int val;

...

scanf("%d", val);
```

使用未初始化变量 Reading Uninitialized Memory

- 假设堆数据初始化为0 Assuming that heap data is initialized to zero

```
/* return y = Ax */
int *matvec(int **A, int *x) {
   int *y = malloc(N*sizeof(int));
   int i, j;

   for (i=0; i<N; i++)
      for (j=0; j<N; j++)
         y[i] += A[i][j]*x[j];
   return y;
}
```

- 使用calloc可以避免 Can avoid by using `calloc`

覆盖内存 Overwriting Memory

- 分配了可能错误大小的对象 **Allocating the (possibly) wrong sized object**

```
int **p;

p = malloc(N*sizeof(int));

for (i=0; i<N; i++) {
   p[i] = malloc(M*sizeof(int));
}
```

- 你能发现这个bug吗？ **Can you spot the bug?**

覆盖内存 Overwriting Memory

- 错位错误 **Off-by-one error**

```
int **p;

p = malloc(N*sizeof(int *));

for (i=0; i<=N; i++) {
    p[i] = malloc(M*sizeof(int));
}
```

```
char *p;

p = malloc(strlen(s));
strcpy(p,s);

```

覆盖内存 Overwriting Memory

- 没有检查最大字符串长度 **Not checking the max string size**

```
char s[8];
int i;

gets(s);  /* reads "123456789" from stdin */
```

- 经典缓冲区溢出攻击的基础 **Basis for classic buffer overflow attacks**

覆盖内存 Overwriting Memory

- 指针运算理解错误 Misunderstanding pointer arithmetic

```
int *search(int *p, int val) {

   while (*p && *p != val)
      p += sizeof(int);

   return p;
}
```

覆盖内存 Overwriting Memory

- 引用了一个指针，而不是其指向的对象 **Referencing a pointer instead of the object it points to**

```
int *BinheapDelete(int **binheap, int *size) {
    int *packet;
    packet = binheap[0];
    binheap[0] = binheap[*size - 1];
    *size--;
    Heapify(binheap, *size, 0);
    return(packet);
}
```

- 减的是什么？ **What gets decremented?**
  - （见下页幻灯片） / (See next slide)

C语言运算符 C operators

后缀 Postfix

一元 Unary　一元 Unary

前缀 Prefix　二元 Binary

二元 Binary

运算符 Operators	*结合性 Associativity*	
`() [] -> . ++ --`	left to right	从左到右
`! ~ ++ -- + - * & (type) sizeof`	right to left	从右到左
`* / %`	left to right	从左到右
`+ -`	left to right	从左到右
`<< >>`	left to right	从左到右
`< <= > >=`	left to right	从左到右
`== !=`	left to right	从左到右
`&`	left to right	从左到右
`^`	left to right	从左到右
`|`	left to right	从左到右
`&&`	left to right	从左到右
`||`	left to right	从左到右
`?:`	right to left	从右到左
`= += -= *= /= %= &= ^= != <<= >>=`	right to left	从右到左
`,`	left to right	从左到右

- **->, ( ) , and [ ] have high precedence ->、()和[]有最高优先级, with * and & just below *、&有次高优先级**
- **一元+、-和*比二元形式有更高优先级 Unary +, −, and * have higher precedence than binary forms**

来源：Source: K&R page 53, updated

覆盖内存 Overwriting Memory

- 引用了一个指针，而不是其指向的对象 **Referencing a pointer instead of the object it points to**

```
int *BinheapDelete(int **binheap, int *size) {
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   binheap[0] = binheap[*size - 1];
   *size--;
   Heapify(binheap, *size, 0);
   return(packet);
}
```

Operators	Associativity
`() [] -> . ++ --`	left to right
`! ~ ++ -- + - * & (type) sizeof`	right to left
`* / %`	left to right
`+ -`	left to right
`<< >>`	left to right
`< <= > >=`	left to right
`== !=`	left to right
`&`	left to right
`^`	left to right
`|`	left to right
`&&`	left to right
`||`	left to right
`?:`	right to left
`= += -= *= /= %= &= ^= != <<= >>=`	right to left
`,`	left to right

- 下面效果相同 **Same effect as**
  - `size--;`
- 应重写为 **Rewrite as**
  - `(*size)--;`

引用不存在的变量 Referencing Nonexistent Variables

- 忘记函数返回之后局部变量不可用 **Forgetting that local variables disappear when a function returns**

```
int *foo () {
   int val;

   return &val;
}
```

多次重复释放块 Freeing Blocks Multiple Times

- 很危险！ **Nasty!**

```
x = malloc(N*sizeof(int));
        <manipulate x>
free(x);

y = malloc(M*sizeof(int));
        <manipulate y>
free(x);
```

引用已经释放的块 Referencing Freed Blocks

- 令人讨厌！ **Evil!**

```
x = malloc(N*sizeof(int));
  <manipulate x>
free(x);
   ...
y = malloc(M*sizeof(int));
for (i=0; i<M; i++)
   y[i] = x[i]++;
```

没有释放内存块（内存泄漏）
Failing to Free Blocks (Memory Leaks)

- 慢性长期的问题 **Slow, long-term killer!**

```
foo() {
   int *x = malloc(N*sizeof(int));
   ...
   return;
}
```

没有释放内存块（内存泄漏）
Failing to Free Blocks (Memory Leaks)

- 只是释放了数据结构的一部分 **Freeing only part of a data structure**

```
struct list {
    int val;
    struct list *next;
};

foo() {
    struct list *head = malloc(sizeof(struct list));
    head->val = 0;
    head->next = NULL;
    <create and manipulate the rest of the list>
      ...
    free(head);
    return;
}
```

应对内存Bug Dealing With Memory Bugs

- **调试器：gdb Debugger: gdb**
  - 能够方便找出问题指针解引 Good for finding bad pointer dereferences
  - 难以探测其他内存问题 Hard to detect the other memory bugs
- **数据结构一致性检查 Data structure consistency checker**
  - 静默运行，出错时打印信息 Runs silently, prints message only on error
  - 用作错误归零的探针 Use as a probe to zero in on error
- **二进制翻译：valgrind Binary translator: `valgrind`**
  - 强大的调试和分析技术 Powerful debugging and analysis technique
  - 重写可执行目标文件的代码段 Rewrites text section of executable object file
  - 运行时检查每个单独的引用 Checks each individual reference at runtime
    - 问题指针、覆盖、越界访问 Bad pointers, overwrites, refs outside of allocated block
- **glibc malloc 包含了检查代码 glibc malloc contains checking code**
  - `setenv MALLOC_CHECK_ 3`