CS 4400
Computer Systems

LECTURE 21

Garbage collection

Memory-related bugs in C

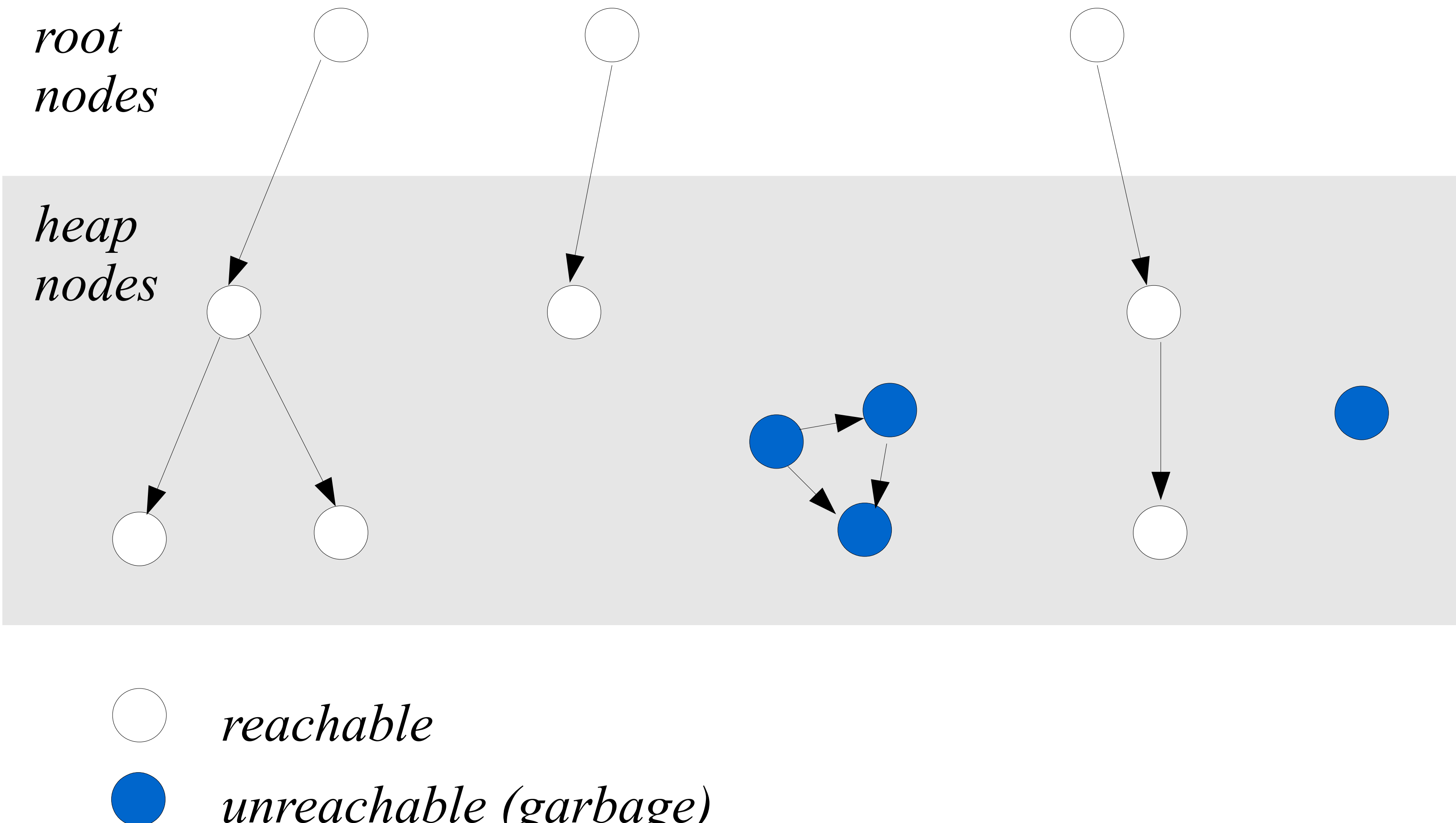
Garbage Collector

- A dynamic storage allocator that automatically frees allocated blocks no longer needed by the program.
  - such blocks are known as *garbage*
- Applications explicitly allocate heap blocks, but never explicitly free them.
- A large number of approaches for garbage collection exist. We'll discuss only the Mark&Sweep algorithm.
- Mark&Sweep can be built on top of an existing `malloc` package to provide garbage collection for C and C++.

Reachability Graph

- Heap nodes correspond to an allocated heap block.
  - $p \rightarrow q$ means that some location in block p points to some location in block q
- Root nodes correspond to locations not in the heap.
  - can be registers, stack variables, ...
- A node p is *reachable* if there exists a directed path from any root node to p.
  - Any unreachable node is garbage.
- The garbage collector must maintain the graph and periodically reclaim unreachable nodes by freeing them.

Example: Reachability Graph



Conservative Garbage Collectors

- Each reachable block is correctly identified as reachable.
- Some unreachable blocks may be incorrectly identified as reachable.
- C/C++ cannot maintain an exact representation of the reachability graph, in general.
  - Thus, collectors for such languages are conservative.
- Collectors can provide their service on demand, or they may run as separate threads in parallel with the program.
  - How can we incorporate a collector into the `malloc` package?

Mark&Sweep

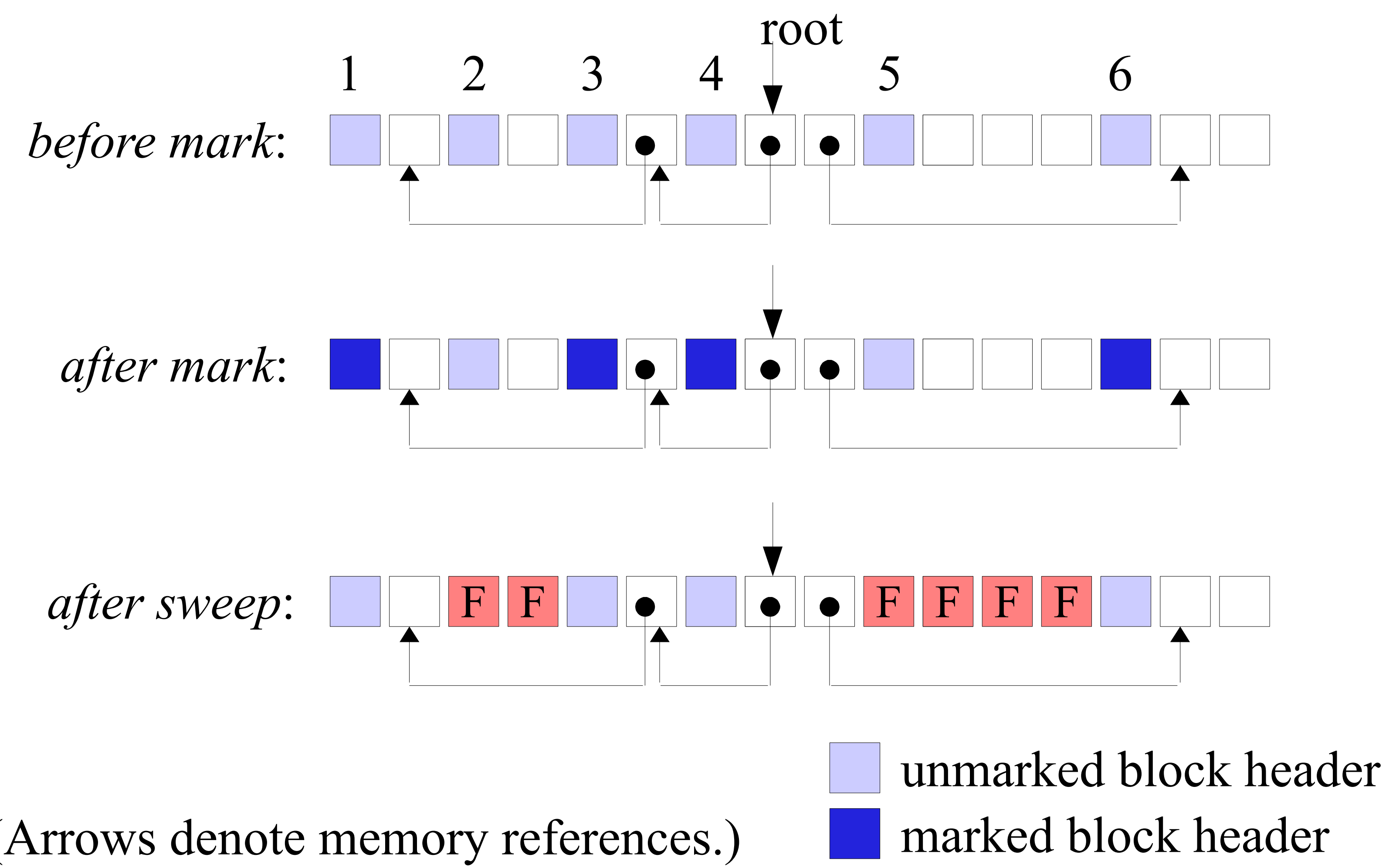
- *Mark phase*—marks all reachable and allocated descendants of the root nodes.
- Calls `mark(p)` for every root node `p`.
  - returns immediately if `p` does not point to an allocated and unmarked heap block
  - otherwise, marks the block and calls itself recursively on each word in the block
- *Sweep phase*—frees each unmarked allocated block.
- Calls `sweep(begin,end)` to iterate over every block in the heap, freeing any unmarked allocated blocks.

Mark&Sweep Pseudocode

```
void mark(ptr p) {
  if((b = isPtr(p)) == NULL)   /* if p points to some */
    return;                    /* word in an allocated */
  if(blockMarked(b))           /* block, isPtr returns */
    return;                    /* a pointer to the */
  markBlock(b);                /* beginning of that block */
  len = length(b);
  for(i = 0; i < len; i++)     /* for every word ... */
    mark(b[i]);
  return;
}

void sweep(ptr b, ptr end) {
  while(b < end) {
    if(blockMarked(b))
      unmarkBlock(b);
    else if(blockAllocated(b))
      free(b);
    b = nextBlock(b);
  }
  return;
}
```

Example: Mark&Sweep



(Arrows denote memory references.)

Initially, the heap consists of 6 unmarked allocated blocks.
After the mark phase, all nodes reachable from the root are marked.
After the sweep phase, unreachable blocks are reclaimed.

Conservative Mark&Sweep

- Implementing `isPtr(p)` in C is a challenge.
- C does not tag memory with any type info.
  - no obvious way to determine if `p` is a pointer
  - what if `int p` has the same value as an allocated address?
- Also, no obvious way to determine if `p` points to some location in the payload of an allocated block.
- A balanced binary search tree of allocated blocks (ordered by address) can help to determine if `p` falls within the extent of an allocated block.

Dereferencing Bad Pointers

- Large holes of virtual memory are not mapped to any meaningful data.
  - dereferencing a pointer into such a hole causes a seg fault
- Some areas of virtual memory are read-only.
  - writing to such an area causes a protection fault
- *Common bug*: `scanf("%d", val); // need &`
  - contents of `val` are interpreted as an address
  - best case—program terminates with an exception
  - worst case—contents of `val` correspond to a valid read/write area of virtual memory (baffling consequences later)

Reading Uninitialized Memory

Unlike `.bss` memory locations, heap memory is not initialized to zero.

```
/* returns y = Ax */
int* matvec(int** A, int* x, int n) {
  int i, j;

  int* y = Malloc(n * sizeof(int));

  for(i = 0; i < n; i++)
    for(j = 0; j < n; j++)
      y[i] += A[i][j] * x[j];

  return y;
}
```

Allowing Stack Buffer Overflows

- Recall that buffer overflow is caused by writing to a target buffer on the stack without examining the size.

```
void bufoverflow() {
  char buf[64];

  gets(buf);
  return;
}
```

- Better to use `fgets(stdin, 64, buf);`

Pointers & Objects Same Size?

- Assuming that pointers and the objects they point to are the same size is a common mistake.

```
/* array of n ptrs, each points to m-int array */
int** makeArray1(int n, int m) {
  int i, **A = Malloc(n * sizeof(int));

  for(i = 0; i < n; i++)
    A[i] = Malloc(m * sizeof(int));

  return A;
}
```

- Runs fine if `int` and `int*` are same size.
- What happens if `int*` is larger?

Off-by-One Errors

```
/* array of n ptrs, each points to m-int array */
int** makeArray2(int n, int m) {
  int i, **A = Malloc(n * sizeof(int*));

  for(i = 0; i <= n; i++)
    A[i] = Malloc(m * sizeof(int));

  return A;
}
```

What happens when we initialize `A[n]`?

Confusing Object & Pointer

- To avoid manipulating a pointer instead of the object it points to, be mindful of operator precedence/associativity.

```
/* remove the first item in a binary heap of
 * size items, then reheapify remaining items */
int* binheapDelete(int** binheap, int* size) {
  int* packet = binheap[0];
  binheap[0] = binheap[*size-1];
  *size--;          /* should be (*size)--; */
  heapify(binheap, *size, 0);
  return packet;
}
```

- What is the consequence of decrementing the pointer instead of the actual size?

Misunderstanding Pointer Arithmetic

- Arithmetic operations on pointers are performed in units that are the size of the objects they (are intended to) point to, not necessarily 1 byte.

```
/* search a 0-terminated array of ints and
   return the first occurrence of val */
int* search(int* p, int val) {
  while(*p && *p != val)
    p += sizeof(int);   /* should be what? */

  return p;
}
```

- Looks only at every fourth integer in the array.

Referencing Nonexistent Vars

```
int* stackref() [
  int val;

  return &val;
}
```

- The function returns a pointer to the local variable and then pops its stack frame. `p=stackref()` remains a valid memory address.
- What happens if the program later assigns some value to `*p`?
- Is there a problem if `val` is `static`?

Referencing Data in Free Blocks

```
int* heapref(int n, int m) {
  int i, *x, *y;

  x = Malloc(n * sizeof(int));
  ...
  free(x);
  ...

  y = Malloc(m * sizeof(int));
  for(i = 0; i < m; i++)
    y[i] = x[i]++;

  return y;
}
```

What are the values in `x`?

Introducing Memory Leaks

- Memory leaks occur when programmers forget to free allocated blocks, inadvertently creating garbage (i.e., unreachable nodes).

```
void leak(int n) {
  int* x = Malloc(n * sizeof(int));

  return;    /* the block at x is now garbage */
}
```

- If this function is called frequently, the heap will gradually fill with garbage (possibly consuming the entire virtual address space).
  - especially important for programs that never terminate

Virtual Memory Summary

- Virtual memory is an abstraction of main memory.
  - DRAM as a cache for disk memory
  - requires translation from virtual address to physical address using page tables, whose contents are maintained by the OS
  - simplifies memory management and protection
- Even though virtual memory is provided automatically by the system, it is a finite resource.
  - managing VM involves subtle time and space trade-offs
- The difficulty of memory-related errors is an important motivation for Java and C#.
  - eliminate the ability to take addresses of variables
  - implicit dynamic storage allocator (no `free` or `delete`)