CS189A - Capstone

Christopher Kruegel
Department of Computer Science
UC Santa Barbara
http://www.cs.ucsb.edu/~chris/

(thanks to George Necula and his CS169 class in Berkeley for the slides)

Outline

- Overview of memory management
  - Why it is a software engineering issue
- Styles of memory management
  - Explicit (malloc/free)
  - Garbage collection
  - Regions
- Detecting memory errors

Memory Management

- A basic decision, because
  - Different memory management policies are difficult to mix
    - Best to stick with one in an application
  - Has a big impact on performance and quality
    - Different strategies better in different situations
    - Some more error prone than others

Distinguishing Characteristics

- Allocation is always explicit
- Deallocation
  - Explicit or implicit?
- Safety
  - Checks that explicit deallocation is safe?

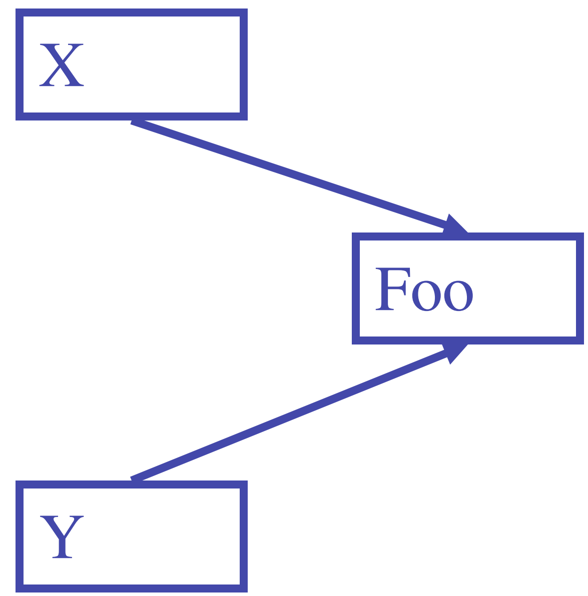
Explicit Memory Management

- Allocation and deallocation are explicit
  - Oldest style
  - C, C++

```
x = new Foo;
…
free(x);
```

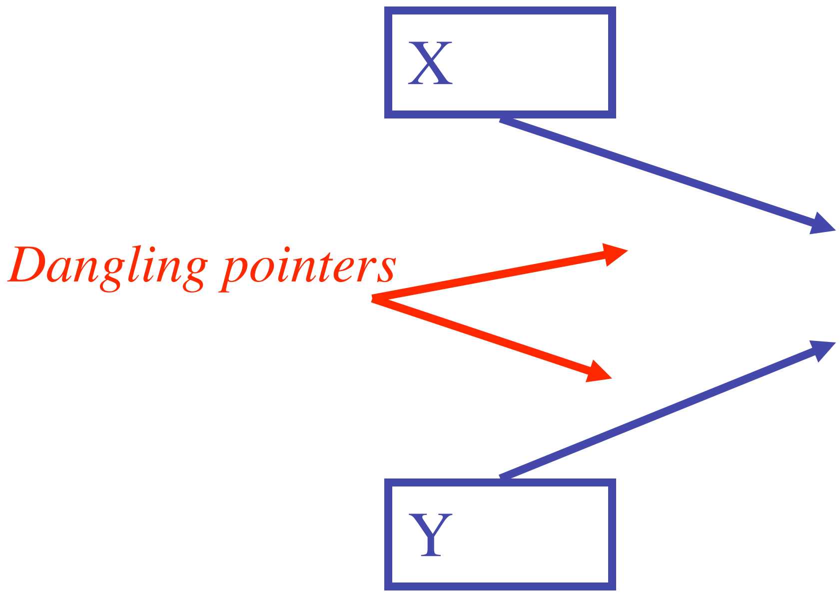
A Problem: Dangling Pointers


```
X = new Foo;
. . .
Y = X;
. . .
delete(X);
. . .
Y.bar();
```



A Problem: Dangling Pointers


```
X = new Foo;
. . .
Y = X;
. . .
free(X);
. . .
Y.bar();
```



Notes

- Dangling pointers are bad
  - A system crash waiting to happen
- Storage bugs are hard to find
  - Visible effect far away (in time and program text) from the source
- Not the only potentially bad memory bug in C

Notes, Continued

- Explicit de-allocation is not all bad
- Gives the finest possible control over memory
  - May be important in memory-limited applications
  - May be important for time-critical, real-time systems
- Programmer is very conscious of how much memory is in use
  - This is good and bad
- Allocation and de-allocation fairly expensive

Automatic Memory Management

- I.e., automatic deallocation

- This is an old problem:
  - studied since the 1950s for LISP

- There are well-known techniques for completely automatic memory management

- Until recently unpopular outside of Lisp family languages
  - introduced to mainstream with Java
  - common in higher-level languages such as Python, …

The Basic Idea

- When an object is created, unused space is automatically allocated
  - E.g., new X
  - As in all memory management systems
- After a while there is no more unused space
- Some space is occupied by objects that will never be used again
  - This space can be freed to be reused later

The Basic Idea (Cont.)

- How can we tell whether an object will "never be used again"?
  - in general, impossible to tell
  - use heuristics
- Observation: a program can use only the objects that it can find:

  A x = new A; x = y; …

  - After x = y there is no way to access the newly allocated object

Garbage

- An object x is reachable if and only if:
  - a register contains a pointer to x, or
  - another reachable object y contains a pointer to x
- You can find all reachable objects by starting from registers and following all the pointers
- An unreachable object can never be used
  - such objects are garbage

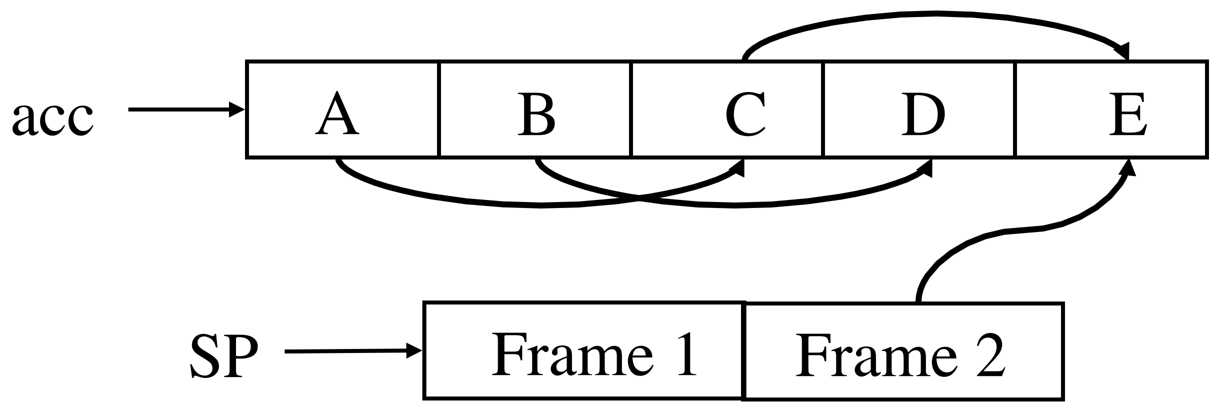
Reachability is an Approximation

- Consider the program:

```
x = new A;
y = new B;
x = y;
if(alwaysTrue()) { x = new A } else { x.foo() }
```

- After x = y (assuming y becomes dead there)
  - the object A is unreachable
  - the object B is reachable (through x)
  - thus B is not garbage and is not collected
    - but object B is never going to be used

A Simple Example



- We start tracing from registers and stack
  - These are the *roots*
- Note B and D are unreachable from acc and stack
  - Thus we can reuse their storage

Elements of Garbage Collection

- Every garbage collection scheme has the following steps
  1. Allocate space as needed for new objects
  2. When space runs out:
     a) Compute what objects might be used again (generally by tracing objects reachable from a set of “root” registers)
     b) Free the space used by objects not found in (a)

- Some strategies perform garbage collection before the space actually runs out

Notes on Garbage Collection

- *Much* safer than explicit memory management
  - Crashes due to memory errors disappear
  - And easy to use

- But exacerbates other problems
  - Memory leaks can be hard to find
    - Because memory usage in general is hidden
  - Different GC approaches have different performance trade-offs

Notes (Continued)

- Fastest GCs do not perform well if live data is significant percentage of physical memory
  - Should be < 30%
  - If > 50%, quite dramatic performance degradation
- Pauses are not acceptable in some applications
  - Use real-time GC, which is more expensive
- Allocation can be very fast
- Amortized deallocation can be very fast, too

A Different Approach: Regions

- Traditional memory management:

	free	GC
Safety	-	+
Control	+	-
Ease of use	-	+
Space usage	+	-

- A different approach: regions

  safety and efficiency, expressiveness

Region-based Memory Management

- Regions represent areas of memory
- Objects are allocated “in” a given region
- Easy to deallocate a whole region

```
Region r = newregion();
for (i = 0; i < 10; i++) {
  int *x = ralloc(r, (i + 1) * sizeof(int));
  work(i, x); }
deleteregion(r);
```

Why Regions ?

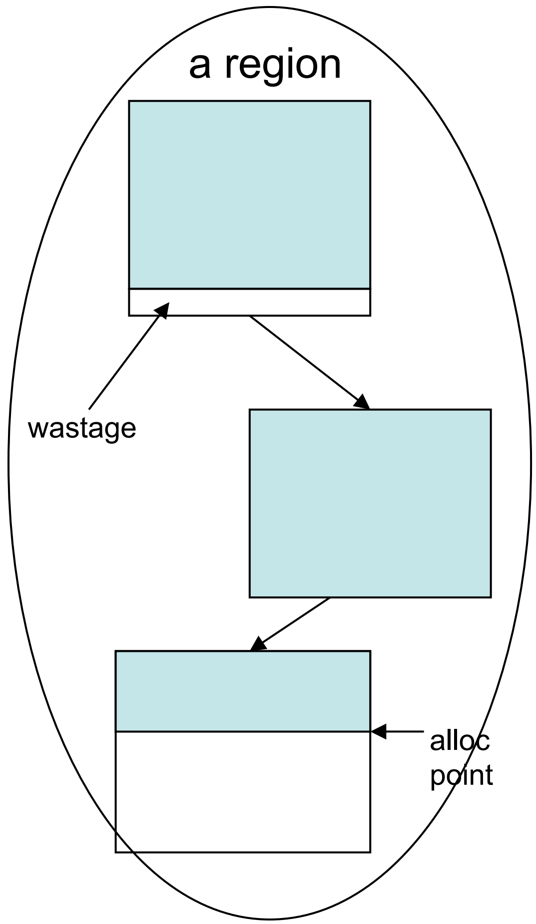
- Performance
- Locality benefits
- Expressiveness
- Memory safety

Region Performance

- Applies to delete all-at-once only

- Basic strategy:
  - Allocate a big block of memory
  - Individual allocation is:
    - pointer increment
    - overflow test
  - Deallocation frees the list of big blocks

- All operations are fast



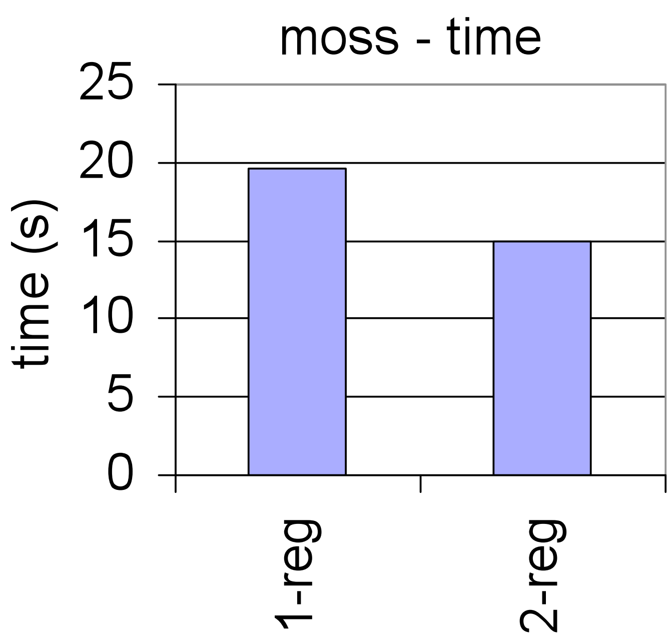
Region Performance: Locality

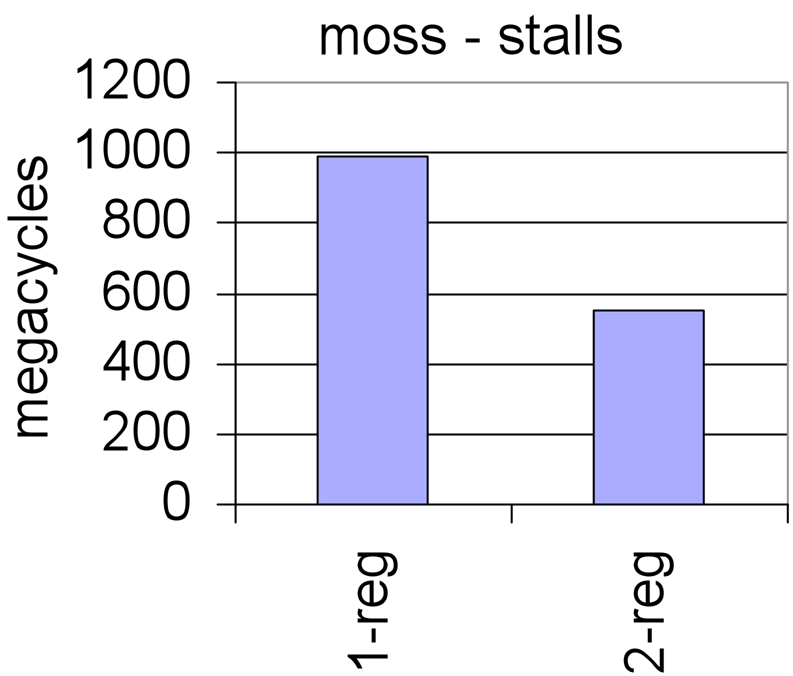
- Regions can express locality:
  - Sequential allocs in a region can share cache line
  - Allocs in different regions less likely to pollute cache for each other

- Example: moss (plagiarism detection software)
  - Small objects: short lived, many clustered accesses
  - Large objects: few accesses

Region Performance: Locality - moss

- 1-region version: small & large objects in 1 region
- 2-region version: small & large objects in 2 regions
- 45% fewer cycles lost to r/w stalls in 2-region version





Region Expressiveness

- Adds some structure to memory management
- Few regions:
  - Easier to keep track of
  - Delay freeing to convenient "group" time
    - End of an iteration, closing a device, etc
- No need to write "free this data structure" functions

Summary

	regions	free	GC
Safety	+	-	+
Control	+	+	-
Ease of use	=	-	+
Space usage	+	+	-
Time	+	+	+

Region Notes

- Regions are fast
  - Very fast allocation
  - Very fast (amortized) deallocation
  - Can express locality
    - Only known technique for doing so

- Good for memory-intensive programs
  - Efficient and fast even if high % of memory in use

Region Notes (Continued)

- Does waste some memory
  - In between malloc/free and GC
- Requires more thought than GC
  - Have to organize allocations into regions

Run-Time Monitoring

- Recall from testing:
  - How do you know that a test succeeds?
  - Can check (intermediate) results, using asserts

- This is called run-time monitoring (RTM)
  - Makes testing more effective

What do we Monitor?

- Check the result of computation
  - E.g., the result of matrix inversion
- Hardware-enforced monitoring
  - E.g., division-by-zero, segmentation fault
- Programmer-inserted monitoring
  - E.g., assert statements

Automated Run-Time Monitoring

- Given a property Q that must hold always
- … and a program P

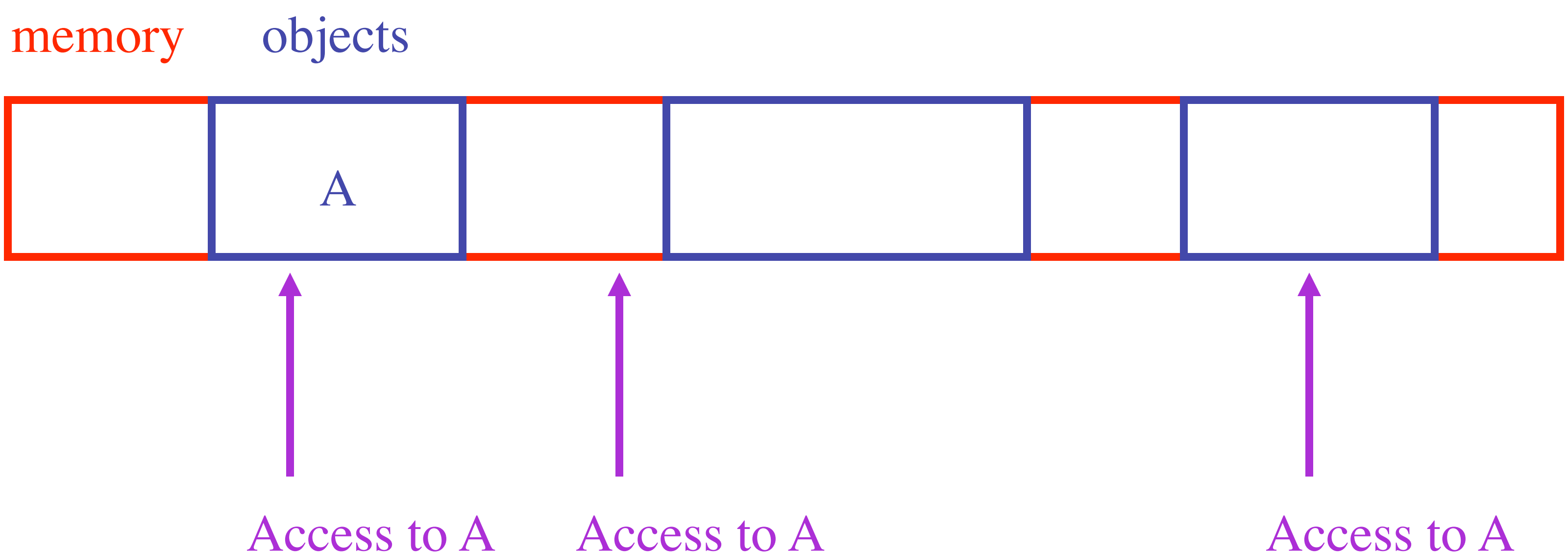
- Produce a program P' such that:
  - P' always produces the same result as P
  - P' has lots of assert(Q) statements, at all places where Q may be violated
  - P' is called the instrumented program

- We are interested in automatic instrumentation

RTM for Memory Safety

- A technique for finding memory bugs
  - Applies to C and C++
- C/C++ are not type safe
  - Neither the compiler nor the runtime system enforces type abstractions
- Possible to read or write outside of your intended data structure

Picture



The Idea

- Each byte of memory is in one of three states:

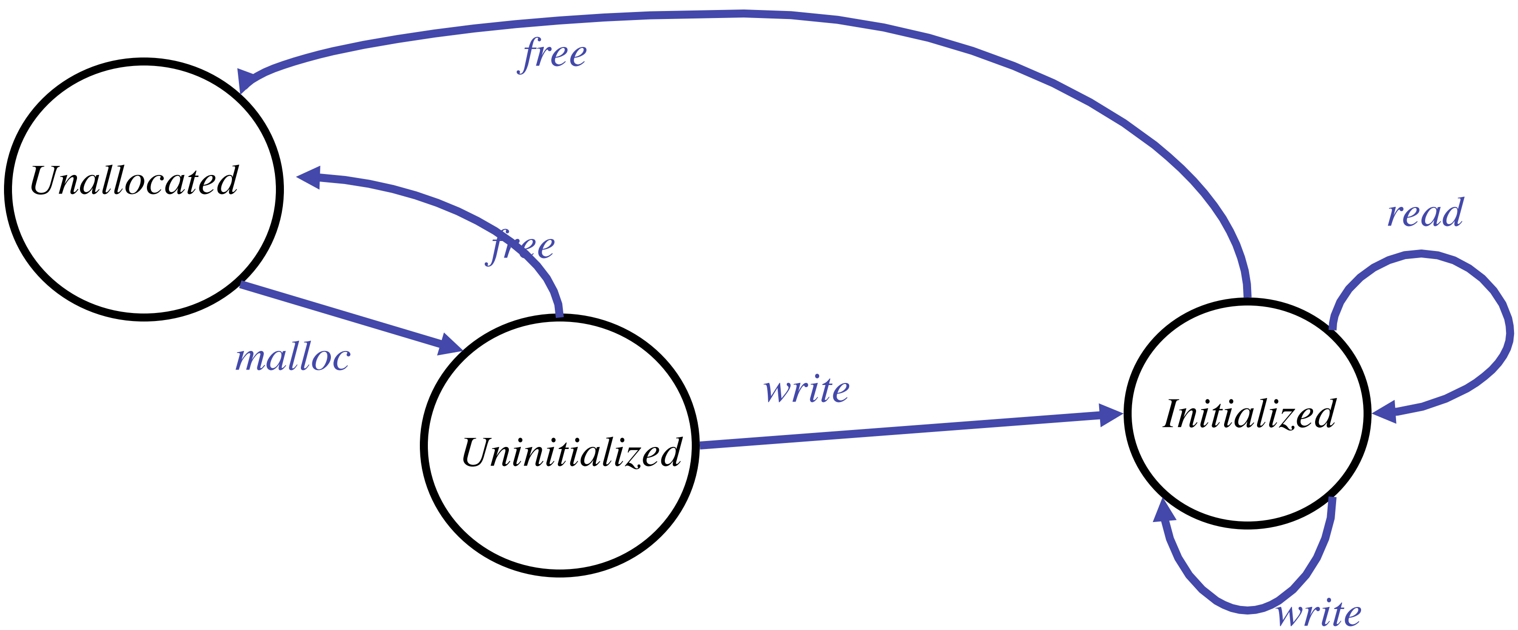
- Unallocated
  - Cannot be read or written

- Allocated but uninitialized
  - Cannot be read

- Allocated and initialized
  - Anything goes

State Machine

Associate an automaton with each byte

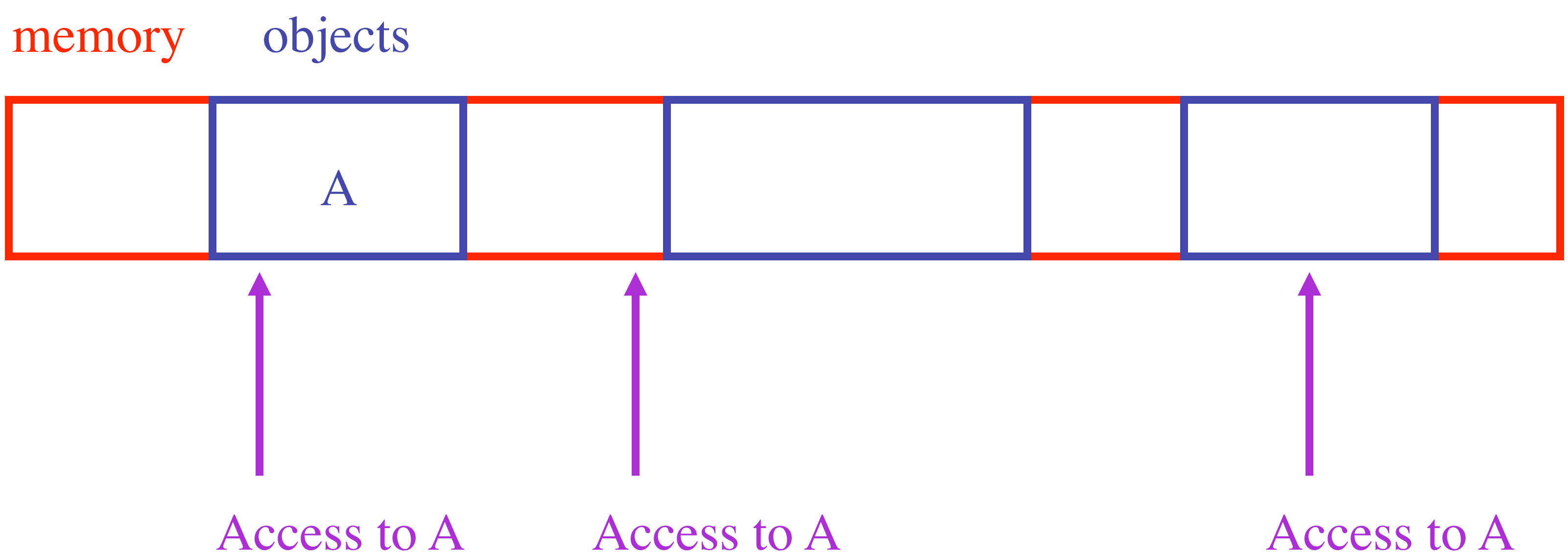


Missing transition edges indicate an error

Instrumentation

- Check the state of each byte on each access
- Binary instrumentation
  - Add code before each load and store
  - Represent states as giant array
    - 2 bits per byte of memory
- 25% memory overhead
  - Catches byte-level errors
  - Won’t catch bit-level errors

Picture



Note: We can detect invalid accesses to red areas, but not to blue areas.

Improvements

- We can only detect bad accesses if they are to unallocated or uninitialized memory
- So try to make most of the bad accesses be of those two forms
  - Especially, the common off-by-one errors

Red Zones

- Leave buffer space between allocated objects
  - The “red zone”
  - In what state do we put this zone?

- Guarantees that walking off the end of an array accesses unallocated memory

Aging Freed Memory

- When memory is freed, do not reallocate immediately
  - Wait until the memory has “aged”
- Helps catch dangling pointer errors
- Red zones and aging are easily implemented in the malloc library

Another Class of Errors: Memory Leaks

- A memory leak occurs when memory is allocated but never freed.
- Memory leaks are at least as serious as memory corruption errors
- We can find many memory leaks using techniques borrowed from garbage collection

The Basic Idea

- Any memory with no pointers to it is leaked
  - There is no way to free this memory
- Run a garbage collector
  - But don't free any garbage
  - Just detect the garbage
  - Any inaccessible memory is leaked memory

Issues with C/C++

- It is sometimes hard to tell what is inaccessible in a C/C++ program
- Cases
  - No pointers to a malloc'd block
    - Definitely garbage
  - No pointers to the head of a malloc'd block
    - Maybe garbage

Leak Detection Summary

- From time to time, run a garbage collector
  - Use mark and sweep
- Report areas of memory that are definitely or probably garbage
  - Need to report who malloc'd the blocks originally
  - Store this information in the red zone between objects

Tools for Memory Debugging

- Purify
  - Robust industrial tool for detecting all major memory faults
  - Developed by Rational, now part of IBM
- Valgrind
  - Open source tool for Linux
  - http://valgrind.org
- “Poor man’s purify”
  - Implement basic memory checking at source code level