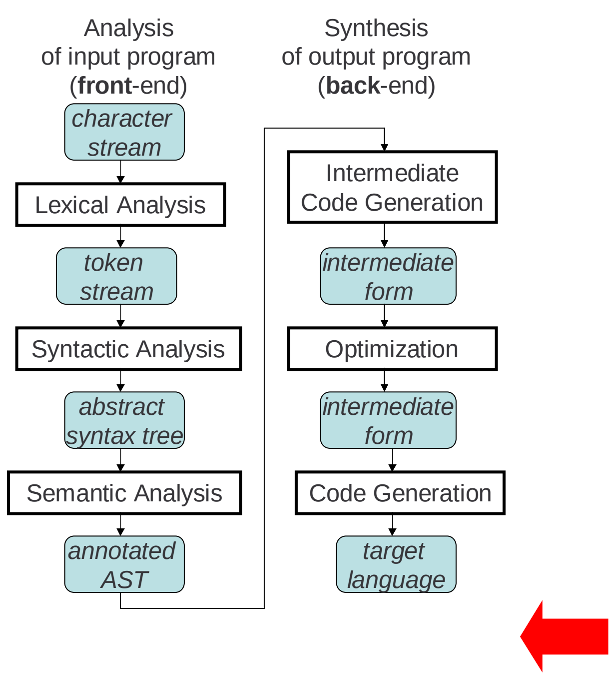
Runtime

The optimized program is ready to run … What sorts of facilities are available at runtime

Compiler Passes



Runtime Systems

Compiled code + runtime system = executable

The runtime system can include library functions for:

- I/O, for console, files, networking, etc.
- graphics libraries, other third-party libraries
- reflection: examining the static code & dynamic state of the running program itself
- threads, synchronization
- memory management
- system access, e.g. system calls

Can have more development effort put into the runtime system than into the compiler!

Memory management

Support

- allocating a new (heap) memory block
- deallocating a memory block when it's done
  - deallocated blocks will be recycled

Manual memory management:

the programmer decides when memory blocks are done, and explicitly deallocates them

Automatic memory management:

the system automatically detects when memory blocks are done, and automatically deallocates them

Manual memory management

Typically use "free lists"

Runtime system maintains a linked list of free blocks

- to allocate a new block of memory, scan the list to find a block that's big enough
  - if no free blocks, allocate large chunk of new memory from OS
  - put any unused part of newly-allocated block back on free list
- to deallocate a memory block, add to free list
  - store free-list links in the free blocks themselves

Lots of interesting engineering details:

- allocate blocks using first fit or best fit?
- maintain multiple free lists, each for different size(s) of block?
- combine adjacent free blocks into one larger block, to avoid fragmentation of memory into lots of little blocks?

See Doug Lea's allocator for an excellent implementation

Regions

A different interface for manual memory management

Support:

- creating a new (heap) memory region
- allocating a new (heap) memory block from a region
- deallocating an entire region when all blocks in that region are done

Deallocating a region is much faster than deallocating all its blocks individually

Less need for complicated reasoning about when individual blocks are done

But must keep entire region allocated as long as any block in the region is still allocated

Best for applications with "phased allocations"

- create a region at the start of a "phase"
- allocate data used only in that phase to the region
- deallocate region when phase completes

(What applications have significant phased allocation?)

Automatic memory management

A.k.a. garbage collection

Automatically identify blocks that are "dead", deallocate them

- ensure no dangling pointers, no storage leaks
- can have faster allocation, better memory locality

General styles:

- reference counting
- tracing
- mark/sweep
- copying

Options:

- generational
- incremental, parallel, distributed

Accurate vs. conservative vs. hybrid

Reference Counting

For each heap-allocated block, maintain count of # of pointers to block

- when create block, ref count = 0
- when create new ref to block, increment ref count
- when remove ref to block, decrement ref count
- if ref count goes to zero, then delete block

Evaluation of reference counting

+ local, incremental work
+ little/no language support required
+ local, implies feasible for distributed systems
- cannot reclaim cyclic structures
- uses malloc/free back-end => heap gets fragmented
- high run-time overhead (10-20%)
  - Delay processing of ptrs from stack (deferred reference counting)
- space cost
- no bound on time to reclaim
- thread-safety?

But: a surprising resurgence in recent research papers fixes almost all of these problems

Tracing Collectors

Start with a set of root pointers

- global vars
- contents of stack and registers

Follow pointers in blocks, transitively starting from blocks pointed at by roots

- identifies all reachable blocks
- all unreachable blocks are garbage
  - unreachable implies cannot be accessed by program

A question: how to identify pointers

- which globals, stack slots, registers hold pointers?
- which slots of heap-allocated memory hold pointers?

Identifying pointers

“Accurate”: always know unambiguously where pointers are

Use some subset of the following to do this:

- static type info & compiler support
- run-time tagging scheme
- run-time conventions about where pointers can be

- Conservative:

  assume anything that looks like a pointer might a pointer,
  & mark target block reachable
  + supports GC in "uncooperative environments", e.g. C, C++

What “looks” like a pointer?

- most optimistic: just align pointers to beginning of blocks
- what about interior pointers? off-the-end pointers? unaligned pointers?

- Miss encoded pointers (e.g. xor’d ptrs), ptrs in files, ...

Mark/sweep collection

- [McCarthy 60]: stop-the-world tracing collector
- Stop the application when heap fills
- Phase 1: trace reachable blocks, using e.g. depth-first traversal
  - set mark bit in each block
- Phase 2: sweep through all of memory
  - add unmarked blocks to free list
  - clear marks of marked blocks, to prepare for next GC

Restart the application

- allocate new (unmarked) blocks using free list

Evaluation of mark/sweep

+ collects cyclic structures
+ simple to implement
+ no overhead during program execution

- “embarrassing pause” problem
- not suitable for distributed systems

Copying collection

Divide heap into two equal-sized **semi-spaces**

- application allocates in **from-space**
- **to-space** is empty

When from-space fills, do a GC:

- visit blocks referenced by roots
- when visit block from pointer:
  - copy block to to-space redirect pointer to copy
  - leave forwarding pointer in from-space version … if visiting block again, just redirect
- scan to-space linearly to visit reachable blocks
  - may copy more blocks to end of to-space a la BFS
- when done scanning to-space
  - reset from-space to be empty
  - **flip**: swap roles of to-space and from-space
- restart application

Evaluation of copying

+ collects cyclic structures
+ allocates directly from end of from-space
  - no free list needed, implies very fast allocation
+ memory implicitly compacted on each allocation
  implies better memory locality
  implies no fragmentation problems
+ no separate traversal stack required
+ only visits reachable blocks, ignores unreachable blocks

- requires twice the (virtual) memory; physical memory sloshes back and forth
  - could benefit from OS support
- “embarrassing pause” problem remains
- copying can be slower than marking
- redirects pointers, implies the need for accurate pointer info

Generational GC

Hypothesis: most blocks die soon after allocation

- e.g. closures, cons cells, stack frames, …

Idea: concentrate GC effort on young blocks

- divide up heap into 2 or more generations
- GC each generation with different frequencies, algorithms

A generational collector

2 generations: new-space and old-space

- new-space managed using copying
- old-space managed using mark/sweep

To keep pauses low, make new-space relatively small

- will need frequent, but short, collections

If a block survives many new-space collections, then promote it to old-space

- no more load on new-space collections

If old-space fills, do a full GC of both generations

Roots for generational GC

Must include pointers from old-space to new-space as roots when collecting new-space

How to find these?

Option 1: scan old-space at each scavenge

Option 2: track pointers from old-space to new-space

Tracking old--> pointers

How to keep track of pointers from old space to new space
- need a data structure to record them in
- need a strategy to update the data structure

Option 0: use a purely functional language!

Option 1: keep list of all locations in old-space with cross-generational pointers
- Instrument all assignments to update list (write barrier)
  - Can implement write barrier in sw or using page-protected hw
  - expensive : duplicates? space?

Option 2: same, but only track blocks containing such locations
- Lower time and space costs, higher root scanning costs

Option 3: track fixed-size **cards** containing such locations
- Use a bit-map as "list," implies very efficient to maintain

Evaluation of generation scavenging

+ new-space collections are short, fraction of a second

+ vs. pure copying:
  - less copying of long-lived blocks
  - less virtual memory space

+ vs. pure mark/sweep:
  - faster allocation
  - better memory locality

- requires write barrier

- still have infrequent full GCs w/embarrassing pauses