Compiler Construction
Lent Term 2015
Lecture 7 (of 16)

- In lecture demo of slang1 compiler
  - http://www.cl.cam.ac.uk/teaching/1415/CompConstr/slang1_compile.tar.gz
  - Jargon virtual machine
    - Uses static links
  - Lambda lifting
    - Slang.1 to Slang.1 transformation.
    - Does not always work. Why?
    - Static links in Jargon are not used lifted code
    - For tricky bits, see lambda_lift.ml

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Lectures 8 and 9 (of 16)

– **Assorted topics**
  - **Bootstrapping**
  - **Garbage collection**

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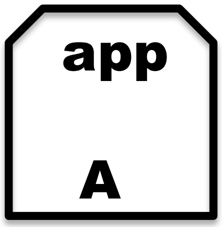
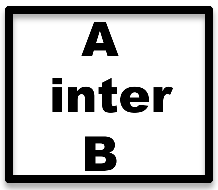
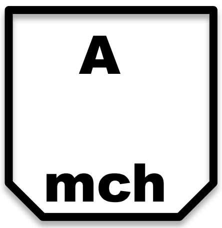
Bootstrapping. We need some notation . . .



An application called **app** written in language **A**

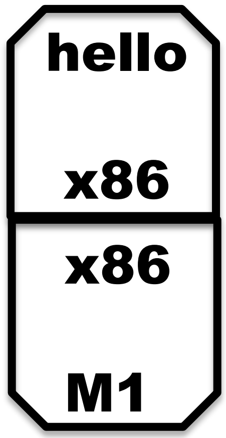


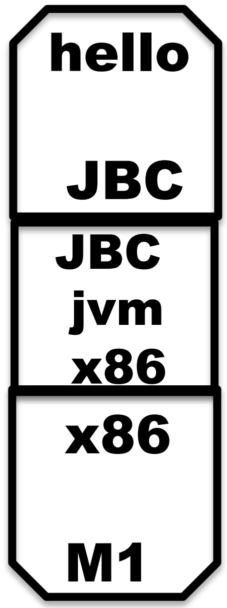
An interpreter or VM for language **A** Written in language **B**



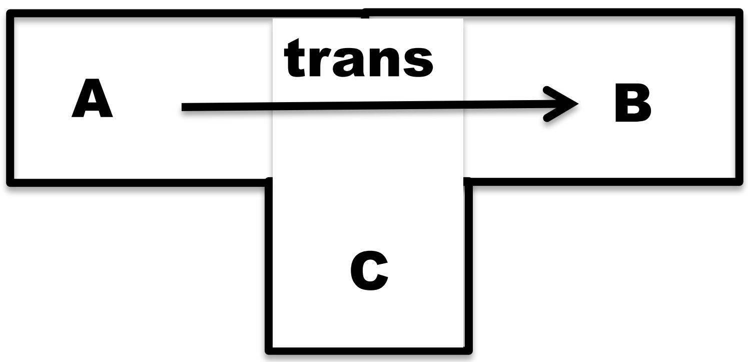
A machine called **mch** running language **A** natively.

Simple Examples



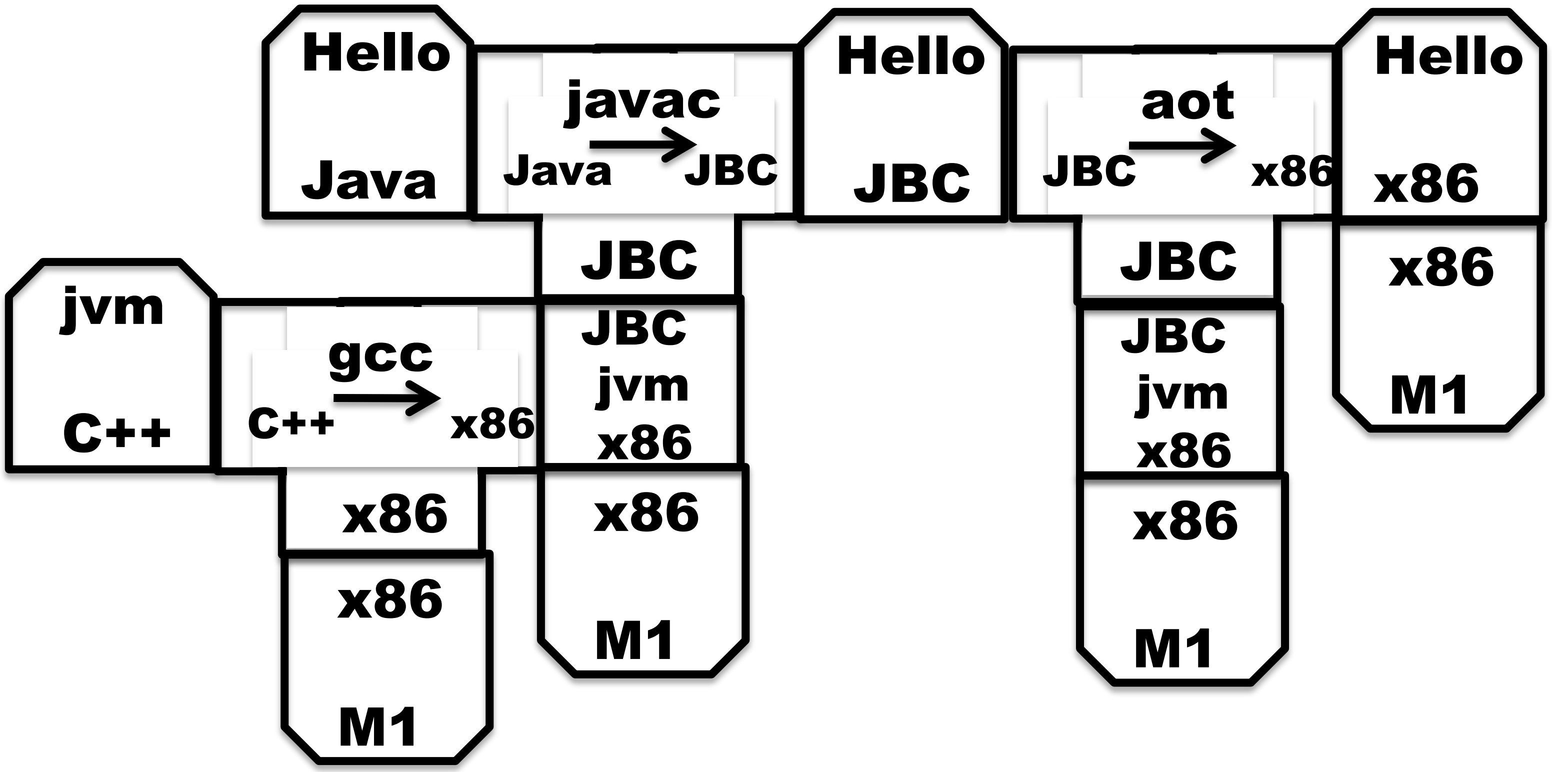


Tombstones



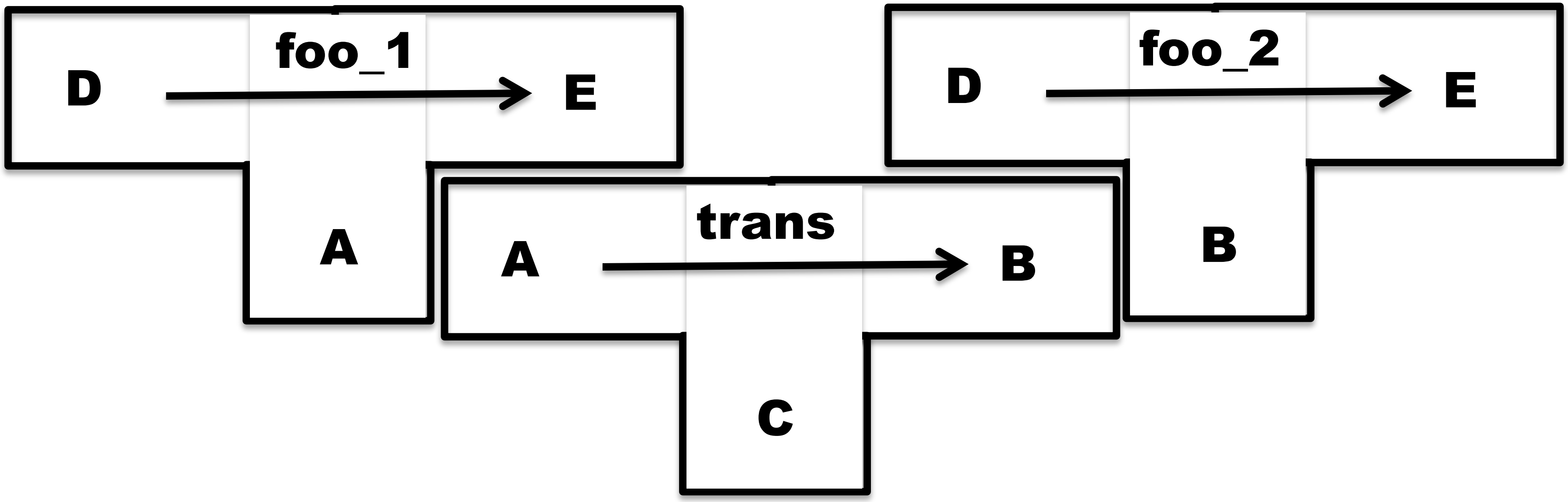
This is an application called **trans** that translates programs in language **A** into programs in language **B**, and it is written in language **C**.

Ahead-of-time compilation



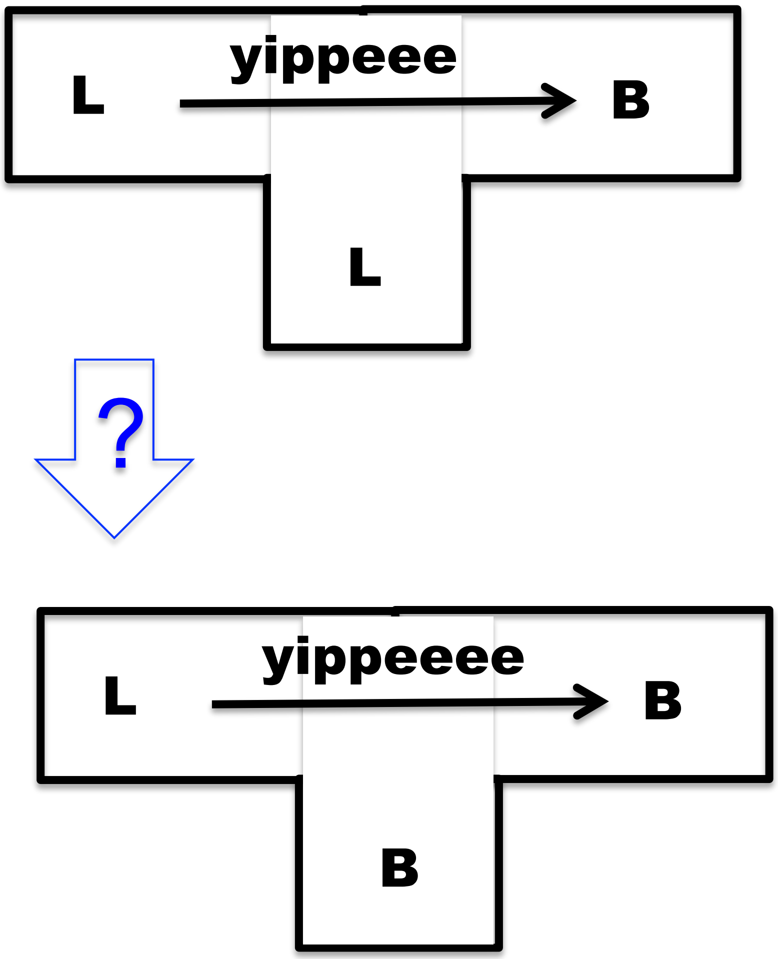
Thanks to David Greaves
for the example.

Of course translators can be translated



Translator **foo_2** is produced as output from **trans** when given **foo_1** as input.

Our seemingly impossible task



We have just invented a really great new language **L** (in fact we claim that "**L** is far superior to C++"). To prove how great **L** is we write a compiler for **L** in **L** (of course!). This compiler produces machine code **B** for a widely used instruction set (say **B** = x86).

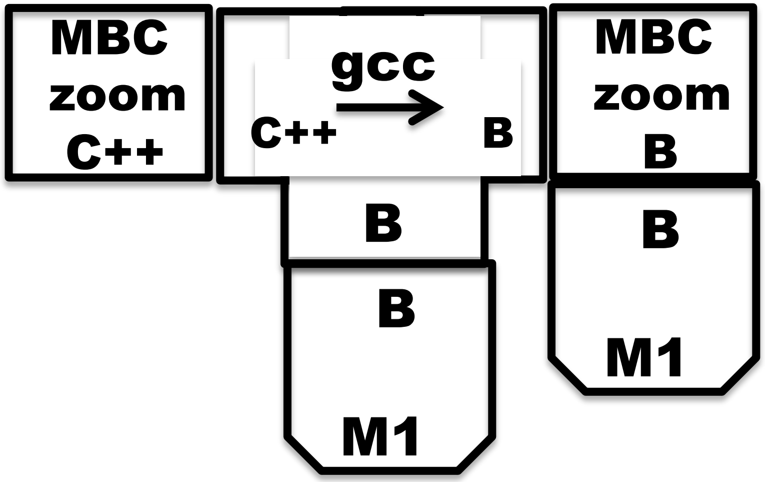
Furthermore, we want to compile our compiler so that it can run on a machine running **B.**

How can we compiler our compiler?

There are many many ways we could go about this task. The following slides simply sketch out one plausible route to fame and fortune.

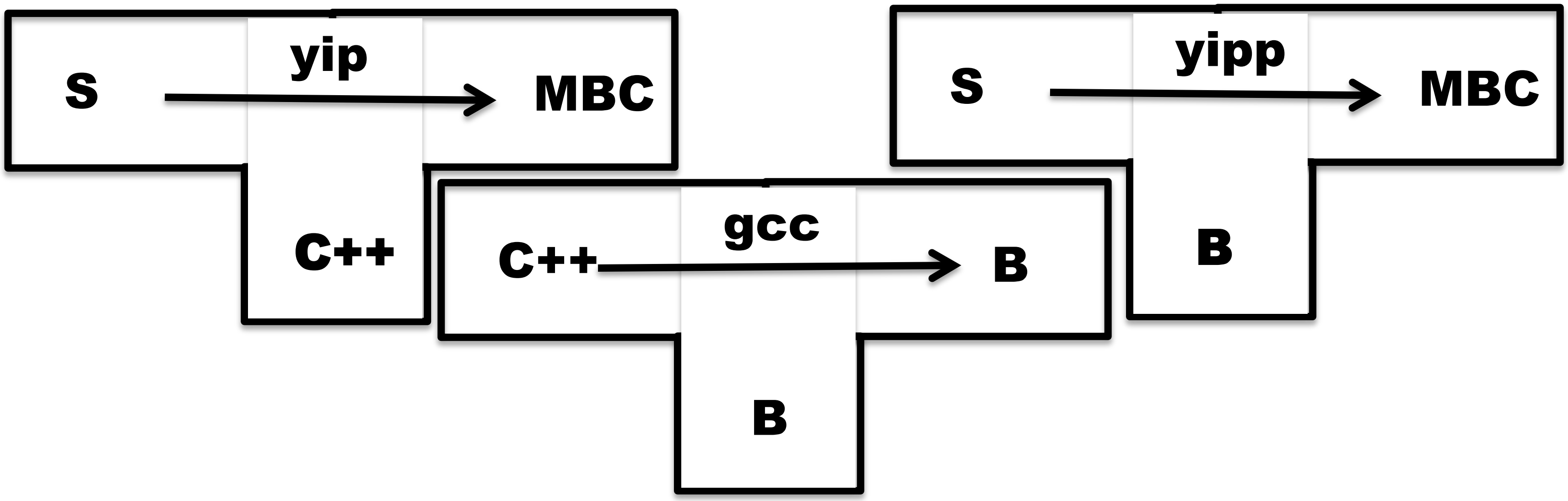
Step 1
Write a small interpreter (VM) for a small language of byte codes

MBC = My Byte Codes



The **zoom** machine!

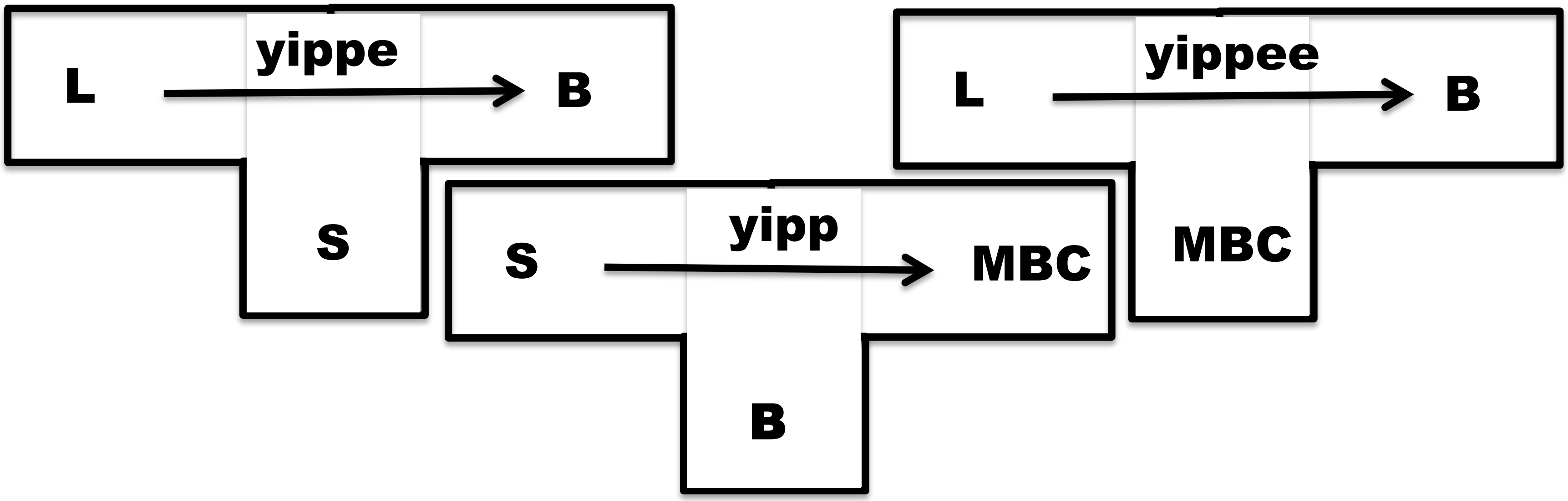
Step 2
Pick a small subset S of L and write a translator from S to MBC



Write **yip** by hand. (It sure would be nice if we could hide the fact that this is written is C++.)

Translator **yipp** is produced as output from **gcc** when **yip** is given as input.

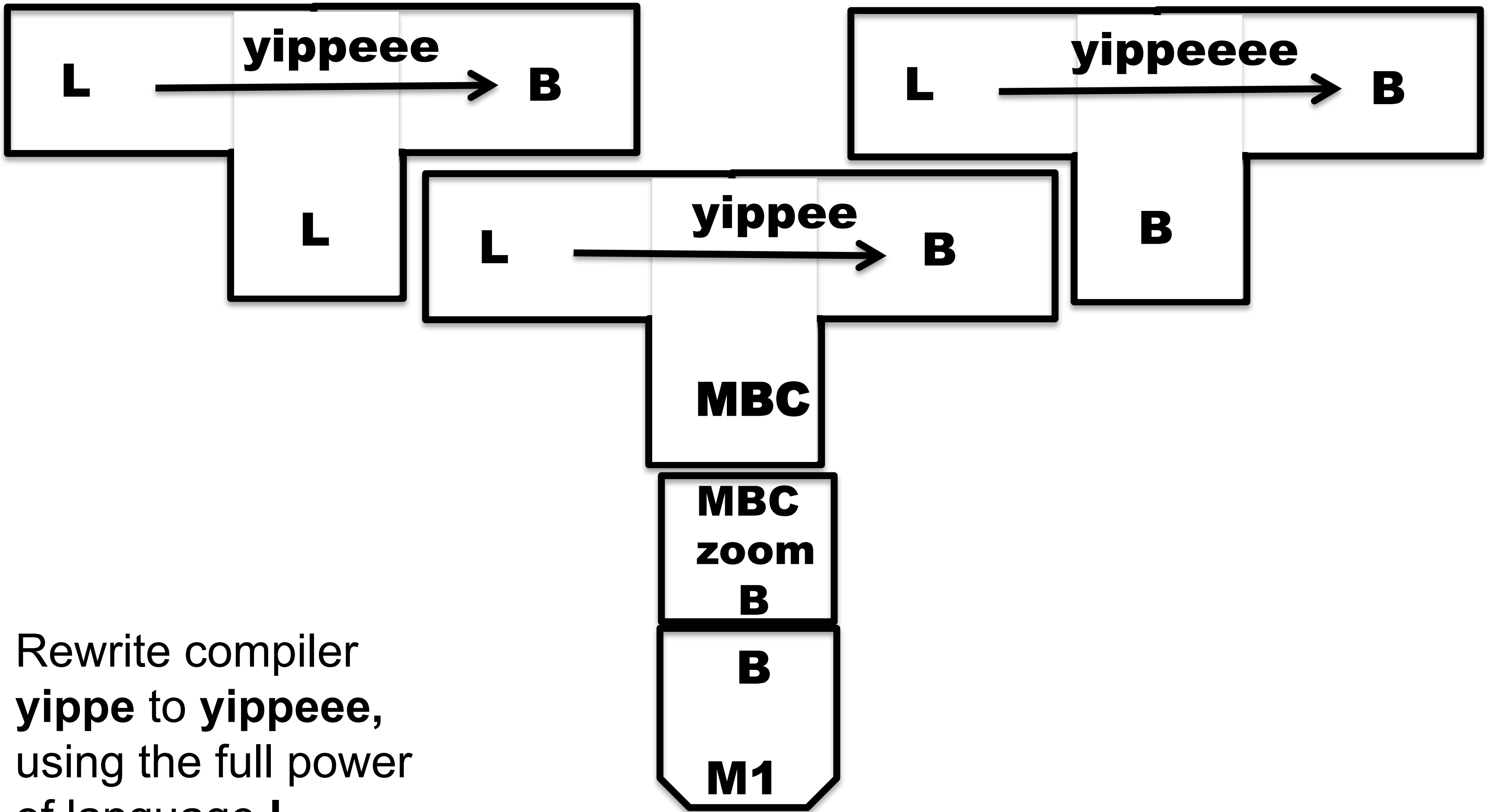
Step 3
Write a compiler for L in S



Write a compiler **yippe** for the full language **L**, but written only in the sub-language **S**.

Compile **yippe** using **yipp** to produce **yippee**

Step 4
Write a compiler for L in L

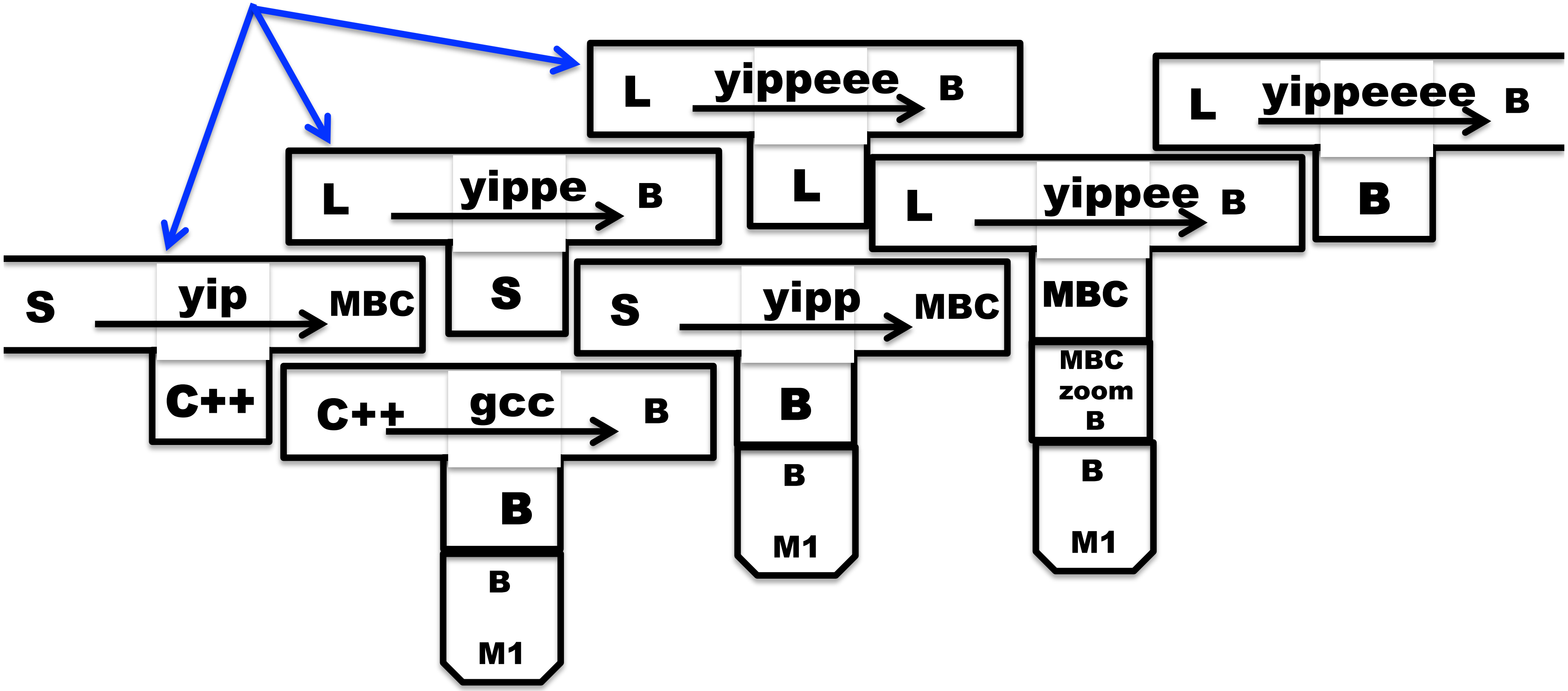


Rewrite compiler **yippe** to **yippeee,** using the full power of language **L**.

Now compile this using **yippee** to obtain our goal!

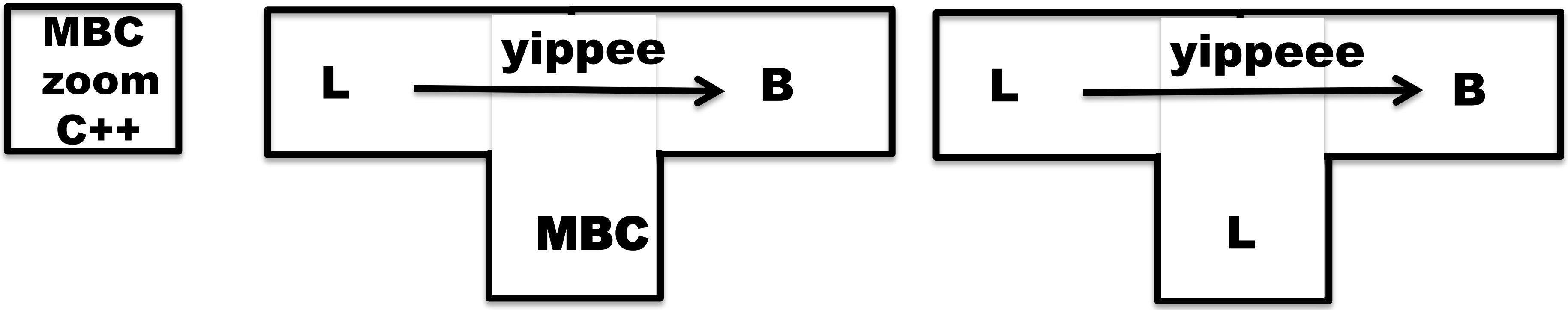
Putting it all together

We wrote only these compilers and the MBC VM.



Step 5 : Cover our tracks and leave the world mystified and amazed

Our **L** compiler download site contains <u>only three</u> components:



yippee is a just file of bytes. We give it the mysterious and intimidating name : **voodoo**

Our instructions:

1. Use **gcc** to compile the **zoom** interpreter
2. Use **zoom** to run **voodoo** with input **yippeee** to output the compiler **yippeeee**

Shhhh! Don't tell anyone that we wrote the first compiler in C++

New topic : Automating run-time memory management

- Managing the heap
- Garbage collection
  - Reference counting
  - Mark and sweep
  - Copy collection
  - Generational collection

Read related chapter of Appel

Memory Management

- Modern programming languages allow programmers to allocate new storage dynamically
  - New records, arrays, tuples, objects, closures, etc.
- Memory could easily be exhausted without some method of reclaiming and recycling the storage that will no longer be used.
  - Let programmer worry about it (use **malloc** and **free** in C…)
  - Automatic “garbage collection”

Solutions

- Let programmer worry about it (use **malloc** and **free** in C…)
- Do nothing
- Automatic memory management ("garbage collection")
  - Reference Counting
  - Mark and Sweep
  - Copy Collection
  - Generational Collection
  - … there are many other GC techniques …

In general, we must approximate since determining exactly what objects will never be used again is **not decidable.**

Explicit Memory Management

- User library manages memory; programmer decides when and where to allocate and de-allocate
  - void* malloc(long n)
  - void free(void *addr)
  - Library calls OS for more pages when necessary
  - Advantage: Gives programmer a lot of control.
  - Disadvantage: people too clever and make mistakes. Getting it right can be costly. And don't we want to automate-away tedium?
  - Advantage: With these procedures we can implement memory management for "higher level" languages ;-)

Automatic Memory Management

Targeting a VM

Generated code

Virtual Machine

Implementation Includes memory management

Targeting a platform

Generated code

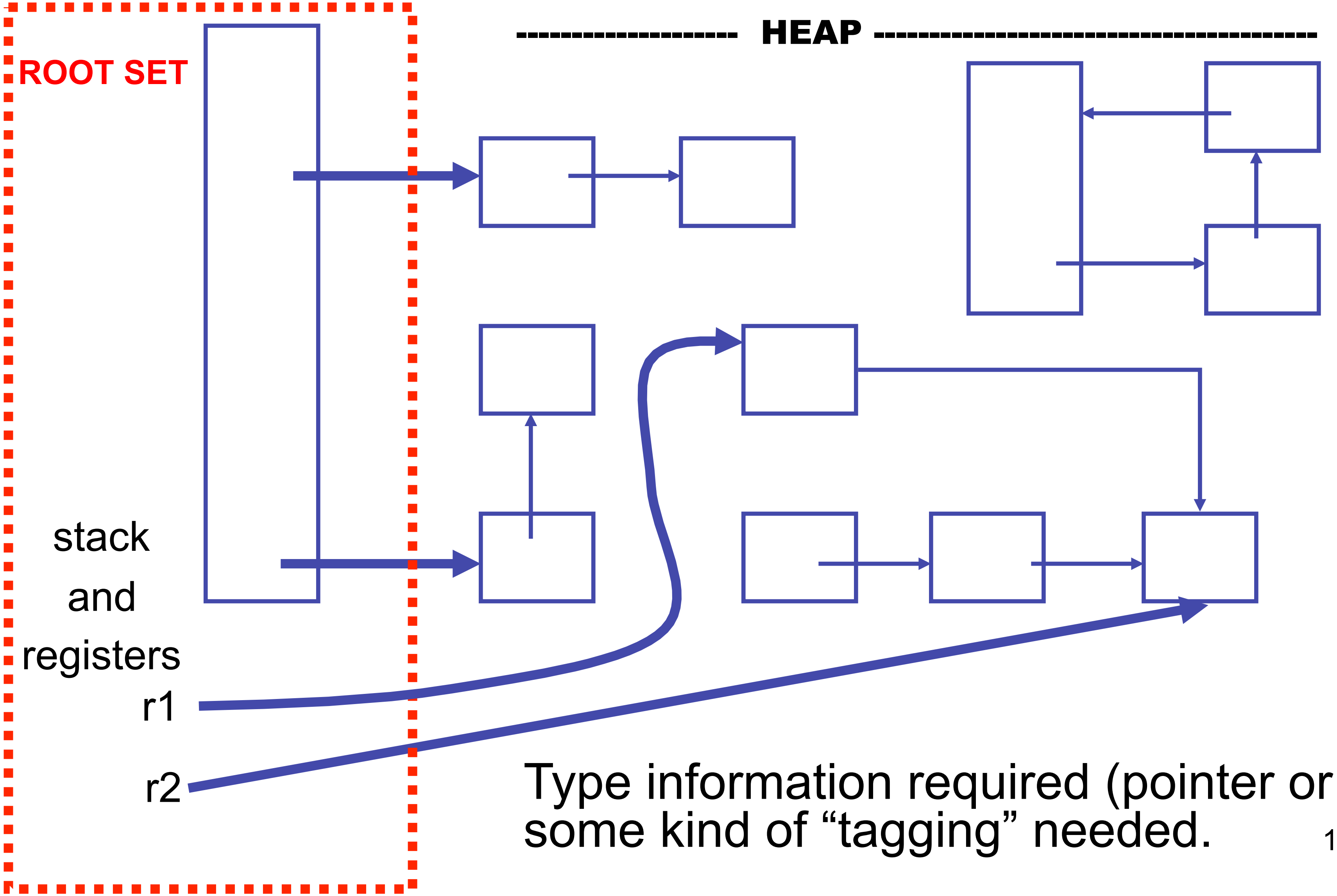
Run-time system, Including memory management

Linker

Executable

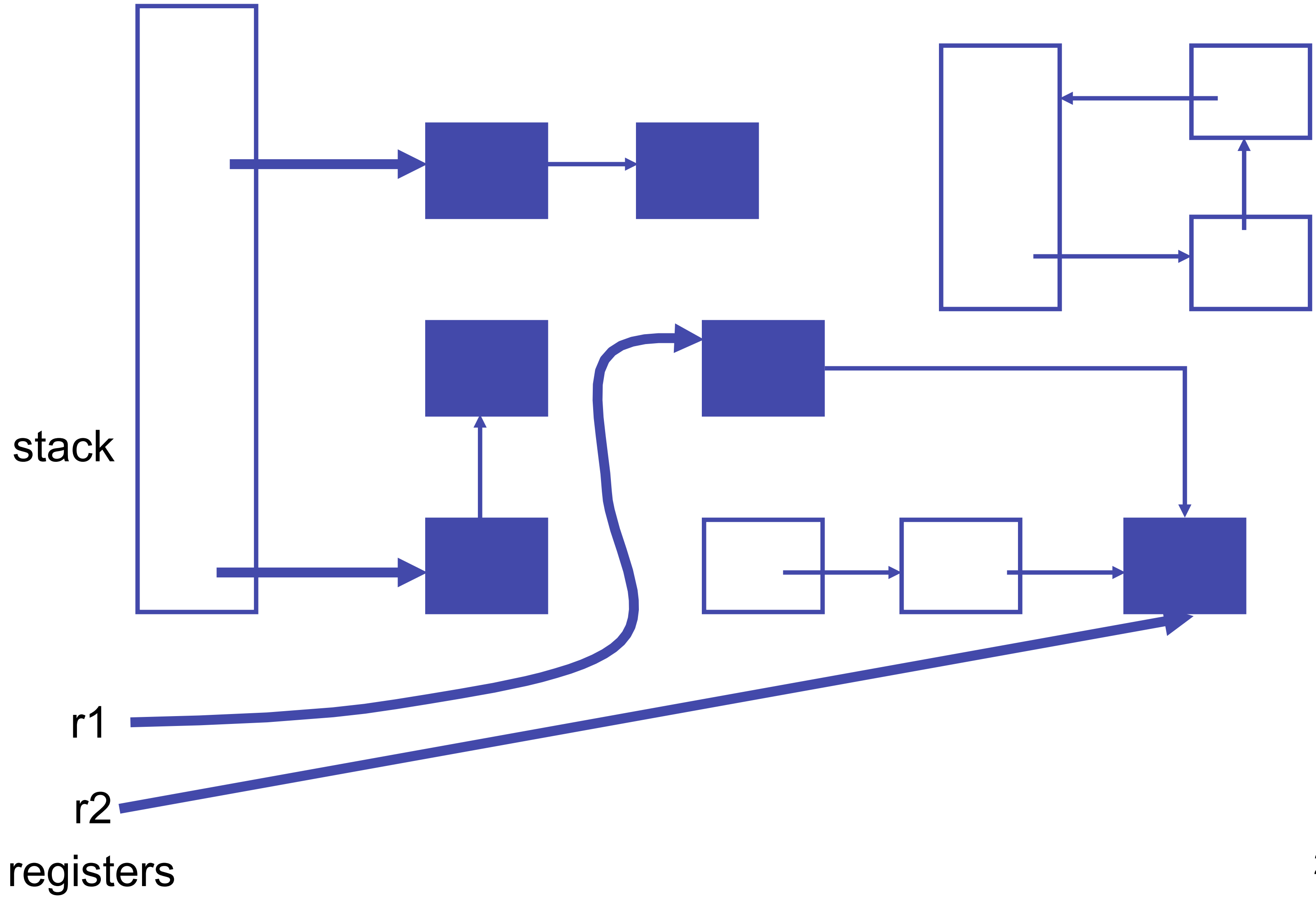
- **When to invoke collection?**
  - **When out of memory?**
  - **When to allocate more space?**
  - **…**

Automation is based on an approximation : if data can be reached from a root set, then it is not "garbage"

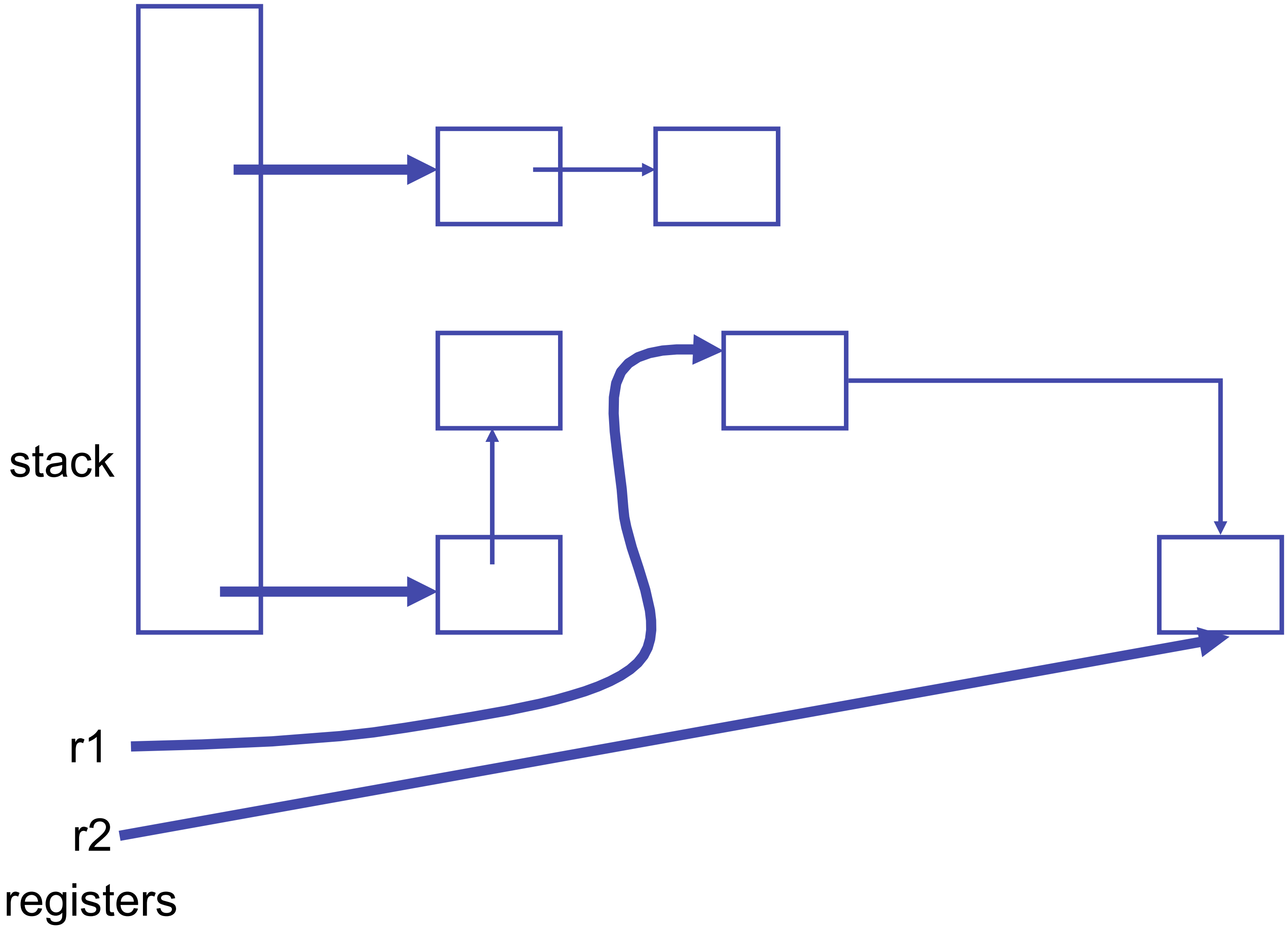


Type information required (pointer or not), some kind of "tagging" needed.

… Identify Cells Reachable From Root Set…



… reclaim unreachable cells



But How? Two basic techniques, and many variations

- **Reference counting** : Keep a reference count with each object that represents the number of pointers to it. Is garbage when count is 0.
- **Tracing** : find all objects reachable from root set. Basically transitive close of pointer graph.

For a very interesting (non-examinable) treatment of this subject see

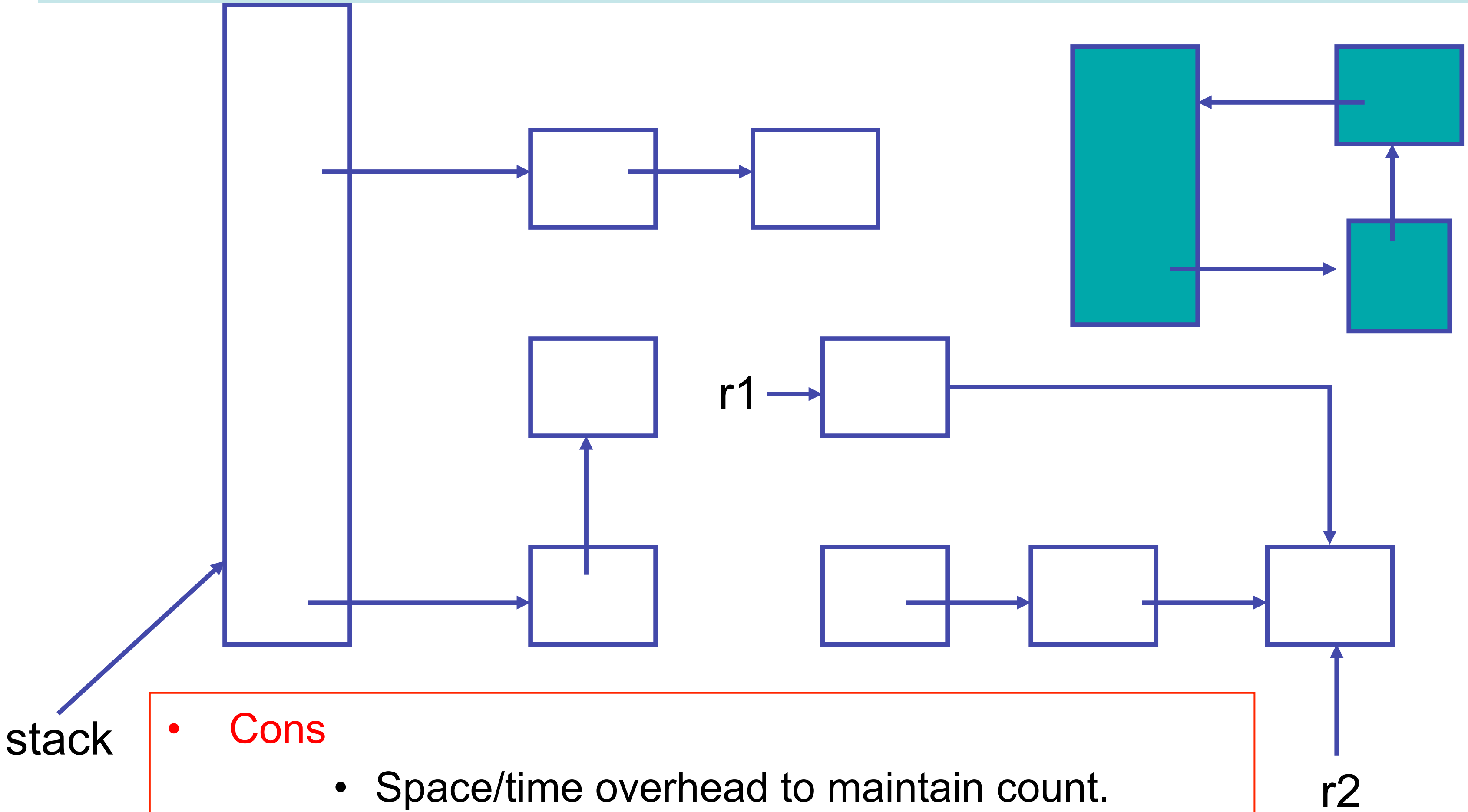
> **A Unified Theory of Garbage Collection**.
> David F. Bacon, Perry Cheng, V.T. Rajan.
> OOPSLA 2004.

In that paper reference counting and tracing are presented as "dual" approaches, and other techniques are hybrids of the two.

Reference Counting, basic idea:

- Keep track of the number of pointers to each object (the reference count).
- When Object is created, set count to 1.
- Every time a new pointer to the object is created, increment the count.
- Every time an existing pointer to an object is destroyed, decrement the count
- When the reference count goes to 0, the object is unreachable garbage

Reference counting can't detect cycles!



- Cons
  - Space/time overhead to maintain count.
  - Memory leakage when have cycles in data.
- Pros
  - <u>Incremental</u> (no long pauses to collect…)

Mark and Sweep

- A two-phase algorithm
  - Mark phase: Depth first traversal of object graph from the roots to mark live data
  - Sweep phase: iterate over entire heap, adding the unmarked data back onto the free list

Cost of Mark Sweep (somewhat crude)

- Cost of mark phase:
  - O(R) where R is the # of reachable words
  - Assume cost is c1 * R (c1 may be 10 instr's)
- Cost of sweep phase:
  - O(H) where H is the # of words in entire heap
  - Assume cost is c2 * H (c2 may be 3 instr's)
- Analysis
  - The "good" = each collection returns H - R words reclaimed
  - Amortized cost = time-collecting/amount-reclaimed
    - ((c1 * R) + (c2 * H)) / (H - R)
    - If R is close to H, then each collection reclaims little space..
  - R / H must be sufficiently small or GC cost is high.

    Could dynamically adjust. Say, if R / H is larger than .5, increase heap size

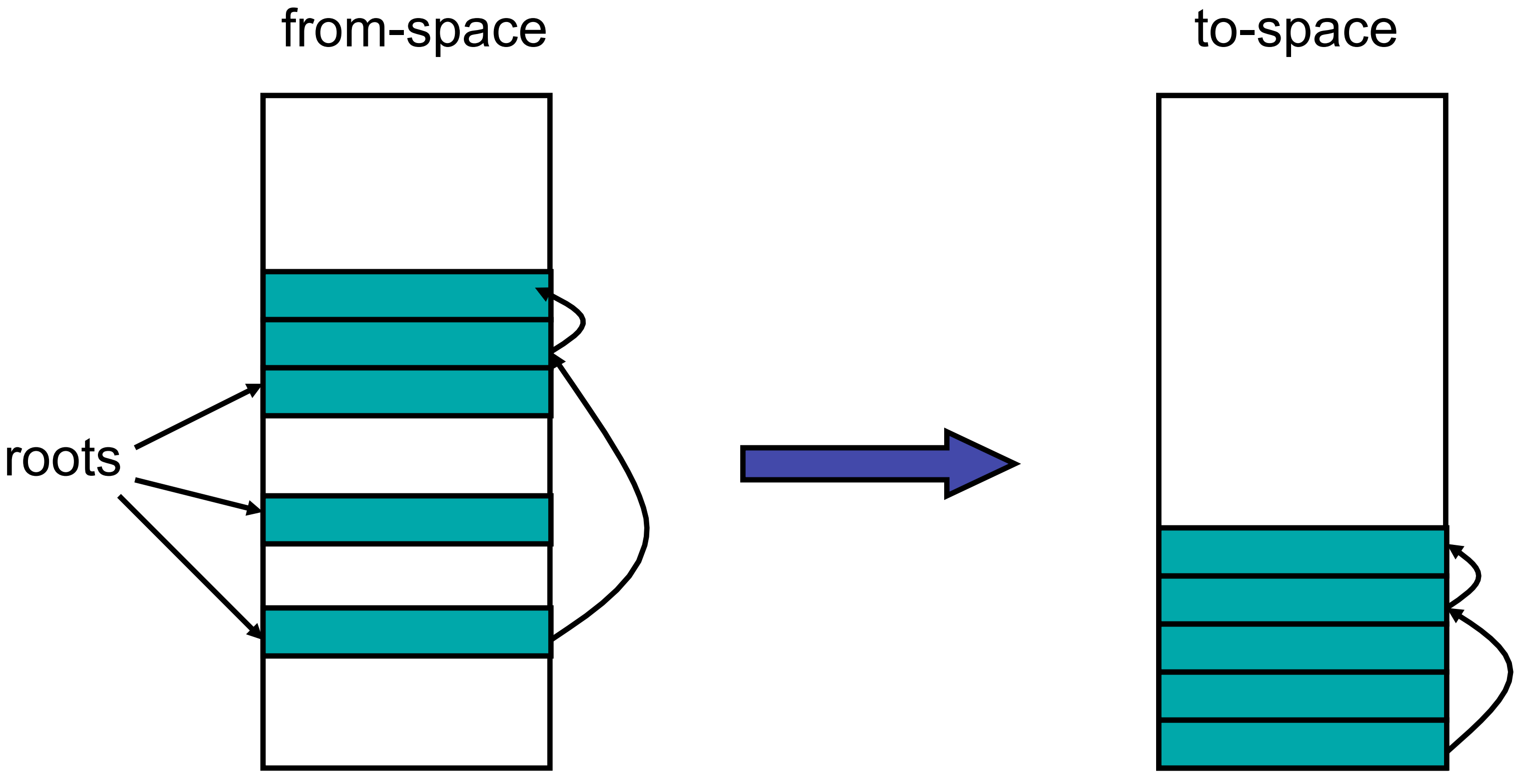
Other Problems

- Depth-first search is usually implemented as a recursive algorithm
  - Uses stack space proportional to the longest path in the graph of reachable objects
    - one activation record/node in the path
    - activation records are big
  - If the heap is one long linked list, the stack space used in the algorithm will be greater than the heap size!!
  - What do we do? Pointer reversal [See Appel]
- Fragmentation

Copying Collection

- Basic idea: use 2 heaps
  - One used by program
  - The other unused until GC time
- GC:
  - Start at the roots & traverse the reachable data
  - Copy reachable data from the active heap (from-space) to the other heap (to-space)
  - Dead objects are left behind in from space
  - Heaps switch roles

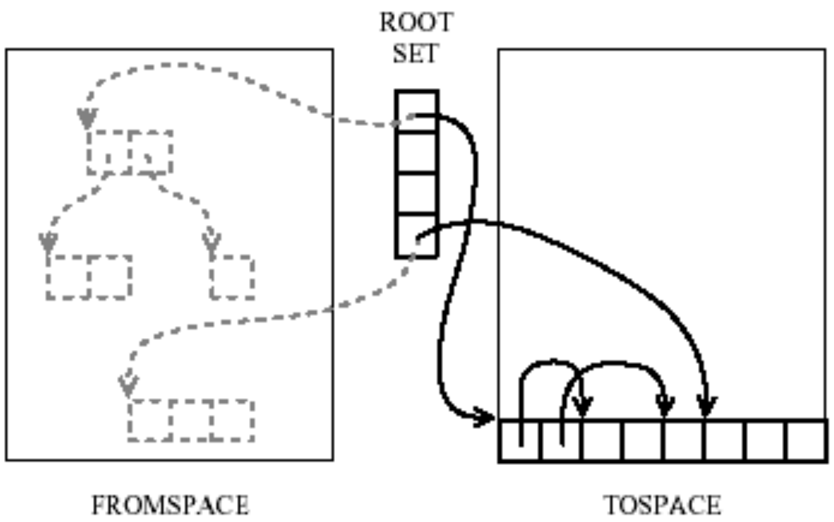
Copying Collection



Copying GC

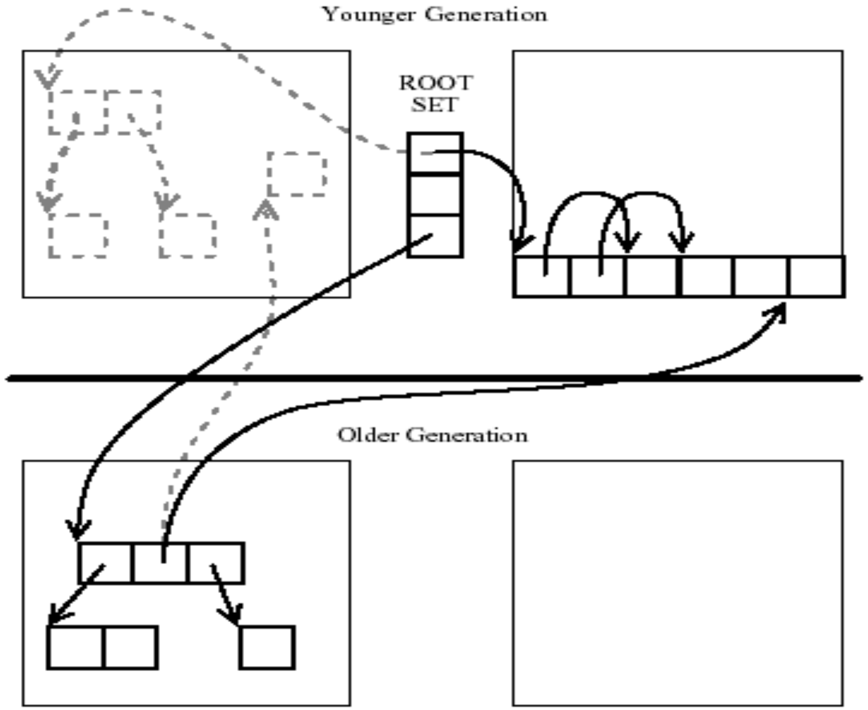
- Pros
  - Simple & collects cycles
  - Run-time proportional to # live objects
  - Automatic compaction eliminates fragmentation
- Cons
  - Twice as much memory used as program requires
    - Usually, we anticipate live data will only be a small fragment of store
    - Allocate until 70% full
    - From-space = 70% heap; to-space = 30%
  - Long GC pauses = bad for interactive, real-time apps

OBSERVATION: for a copying garbage collector



- 80% to 98% new objects die very quickly.
- An object that has survived several collections has a bigger chance to become a long-lived one.
- It's a inefficient that long-lived objects be copied over and over.

IDEA: Generational garbage collection



Segregate objects into multiple areas by age, and collect areas containing older objects less often than the younger ones.

Other issues...

- When do we promote objects from young generation to old generation
  - Usually after an object survives a collection, it will be promoted
- Need to keep track of older objects pointing to newer ones!
- How big should the generations be?
  - Appel says each should be exponentially larger than the last
- When do we collect the old generation?
  - After several minor collections, we do a major collection
- Sometimes different GC algorithms are used for the new and older generations.
  - Why? Because the have different characteristics
  - Copying collection for the new
    - Less than 10% of the new data is usually live
    - Copying collection cost is proportional to the live data
  - Mark-sweep for the old