Runtime System

COMP 524: Programming Language Concepts
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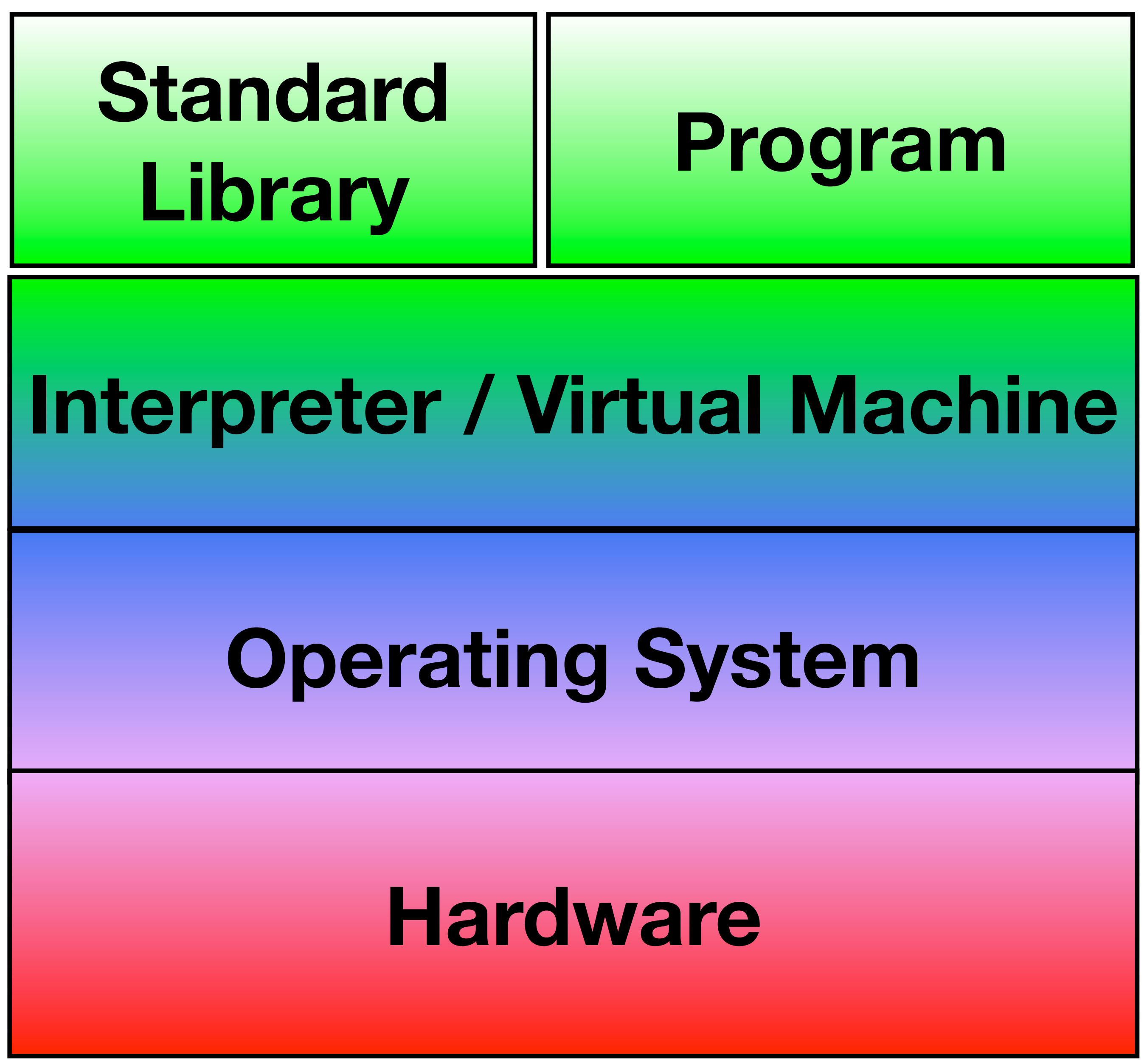
Based in part on slides and notes by S. Olivier, A. Block, N. Fisher, F. Hernandez-Campos, and D. Stotts.

What is the Runtime System (RTS)?

Language runtime environment.

- **OS view**: RTS is part of the user program.
- But RTS was **not programmed by the language user**.
- The RTS is everything not part of the OS and not explicitly provided by the user (i.e., the program or 3rd party libraries).



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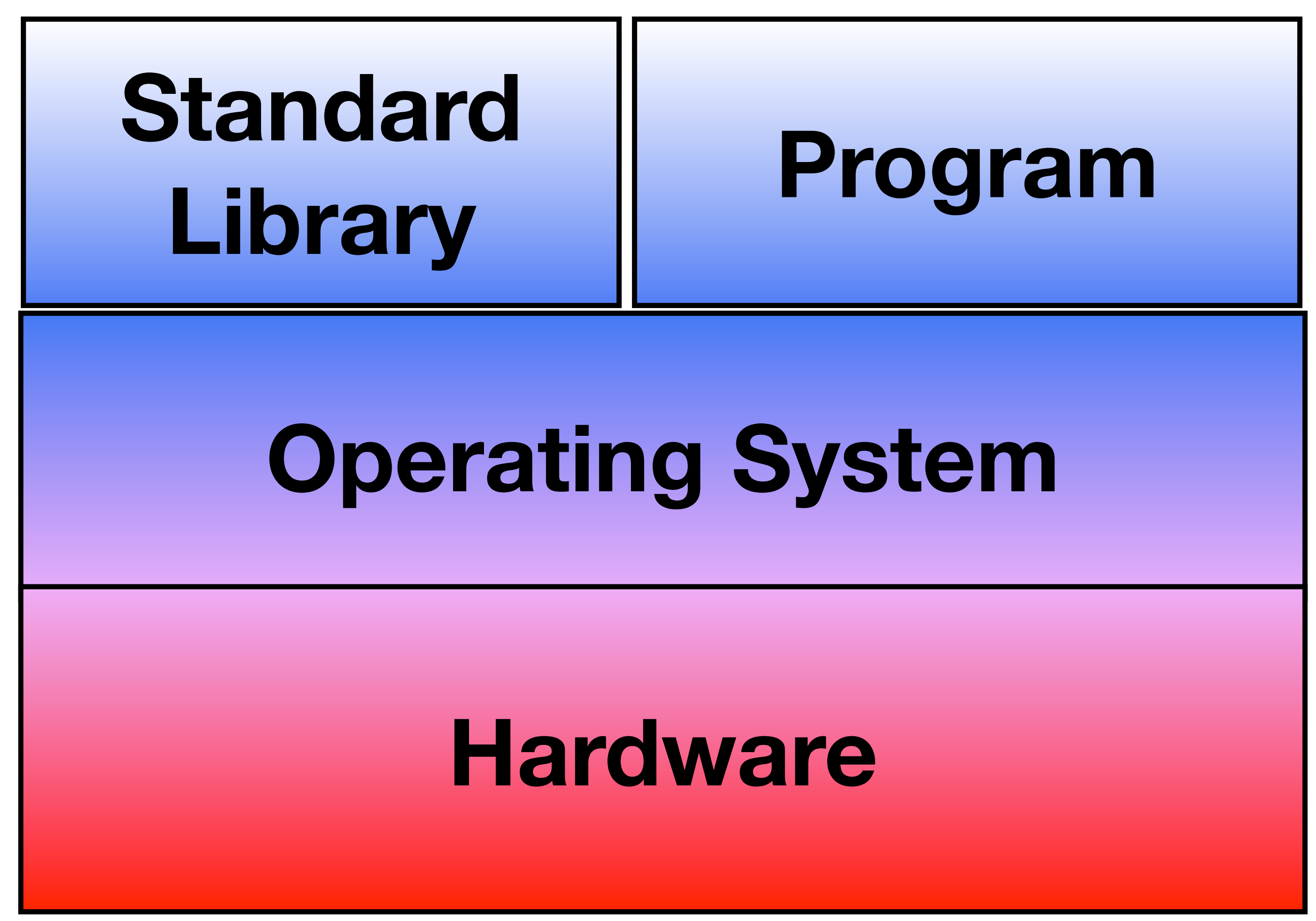

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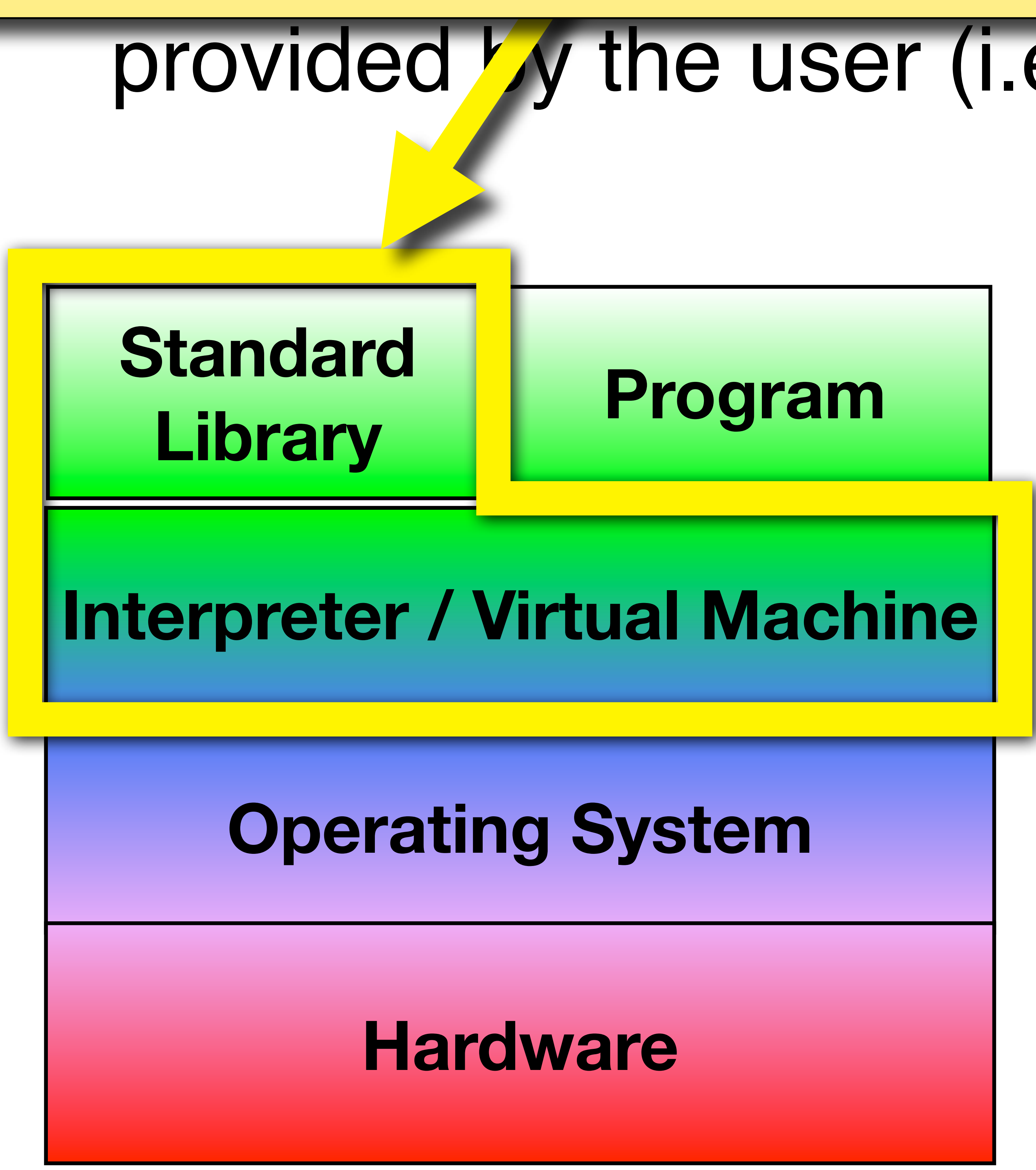
Examples: memory allocator, **garbage collector**, support for runtime casts, exception handling infrastructure, **just-in-time (JIT) compiler**, support for closure and anonymous functions, lazy evaluation, dynamic type checking, byte code verifier, OS abstraction layers (if any), class-loading and plugin support (if any), multi-threading support, remote procedure calls (e.g., Java RMI), …

provided by the user (i.e., the program or 3rd party libraries).



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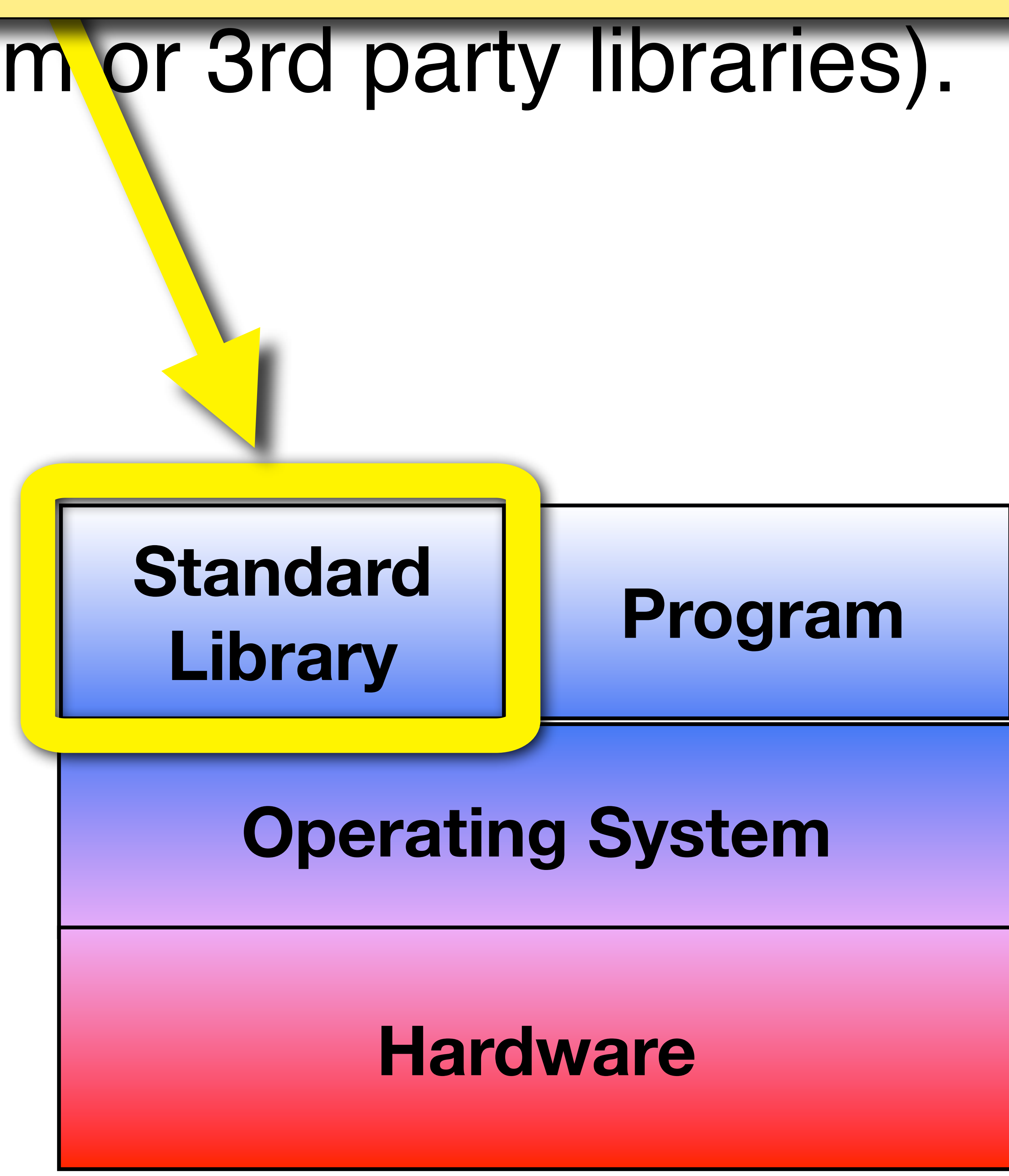

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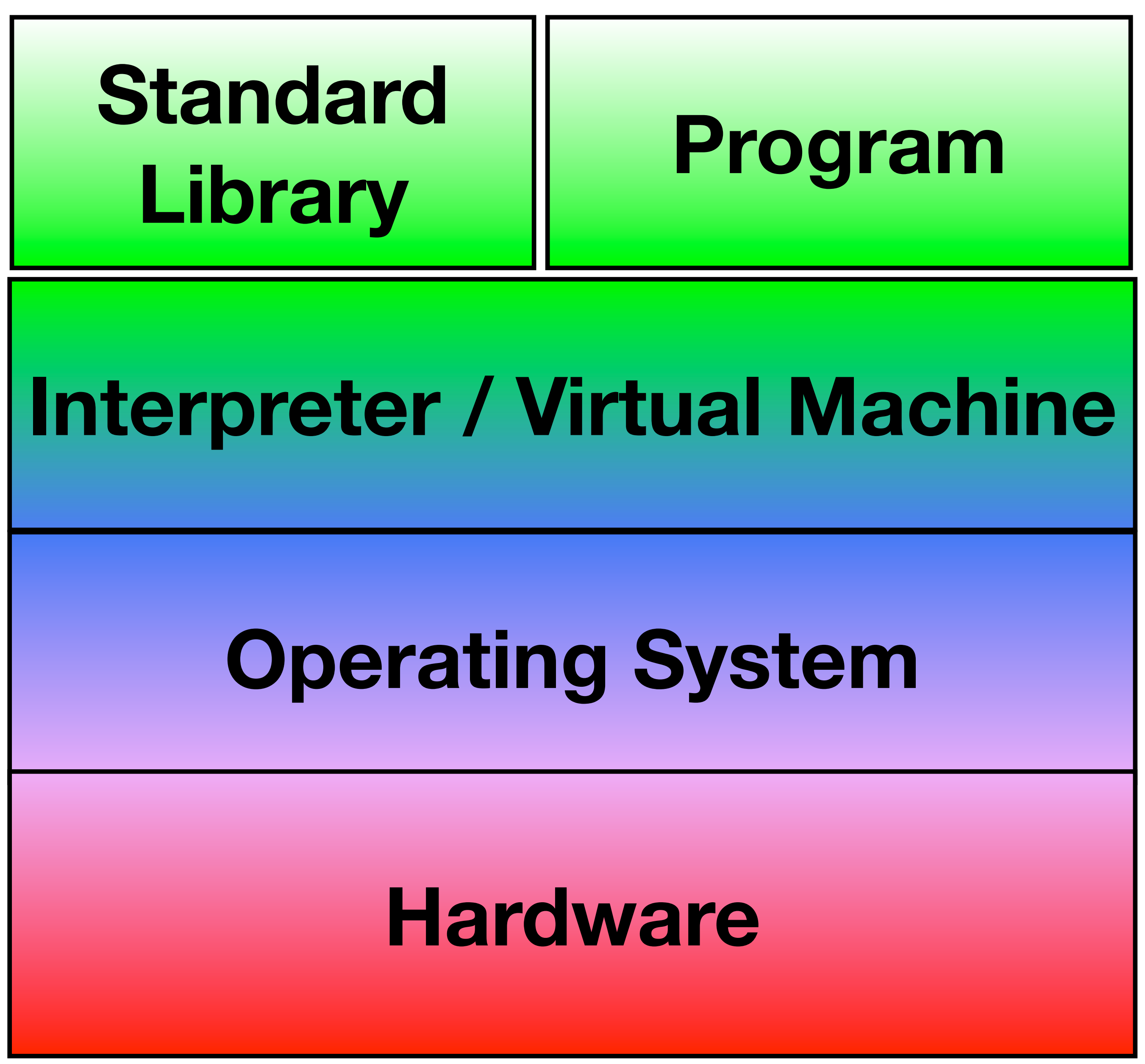
What is the Runtime System (RTS)?

RTS:
the infrastructure required to (transparently) realize **higher-level language abstractions** at runtime.



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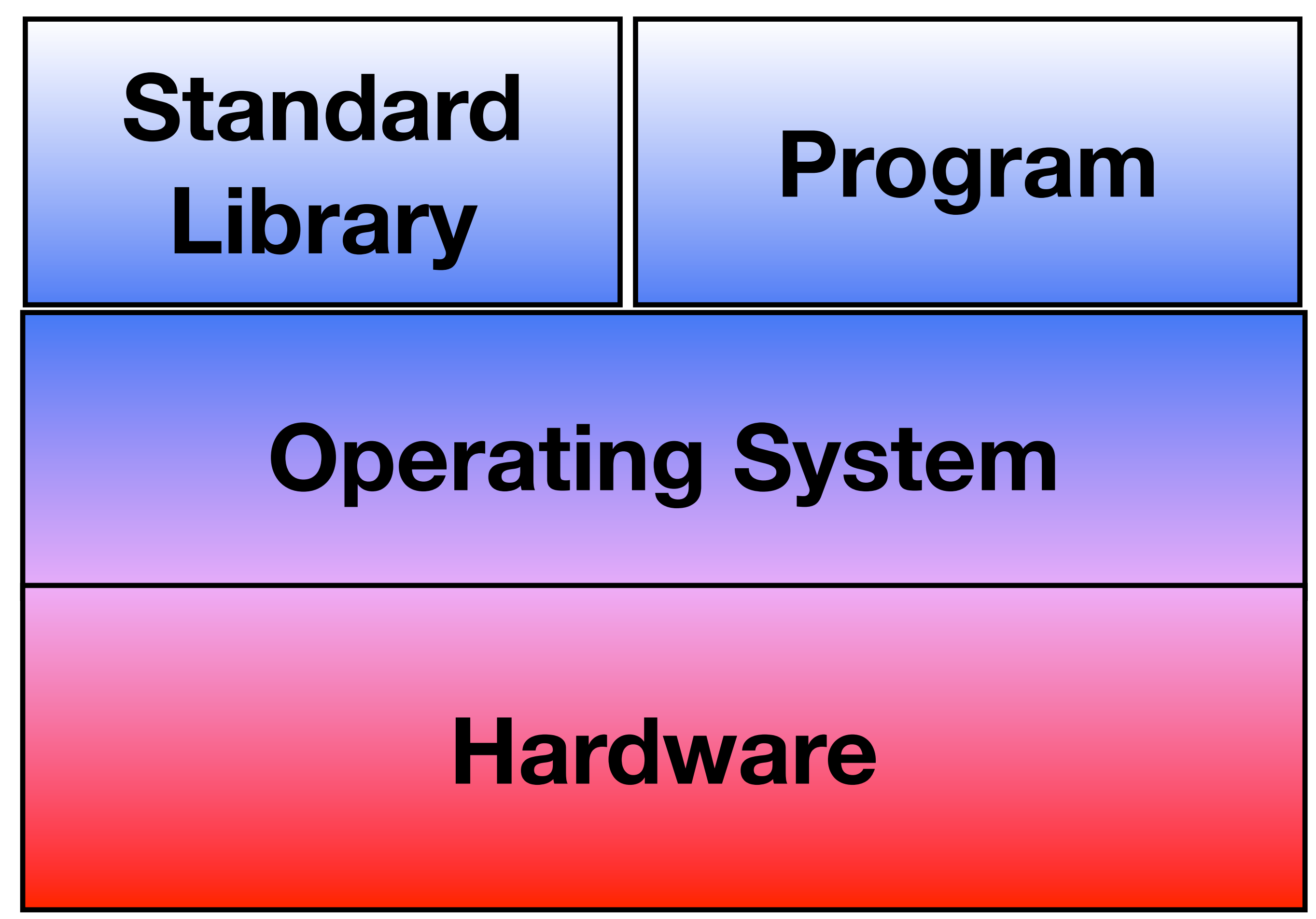

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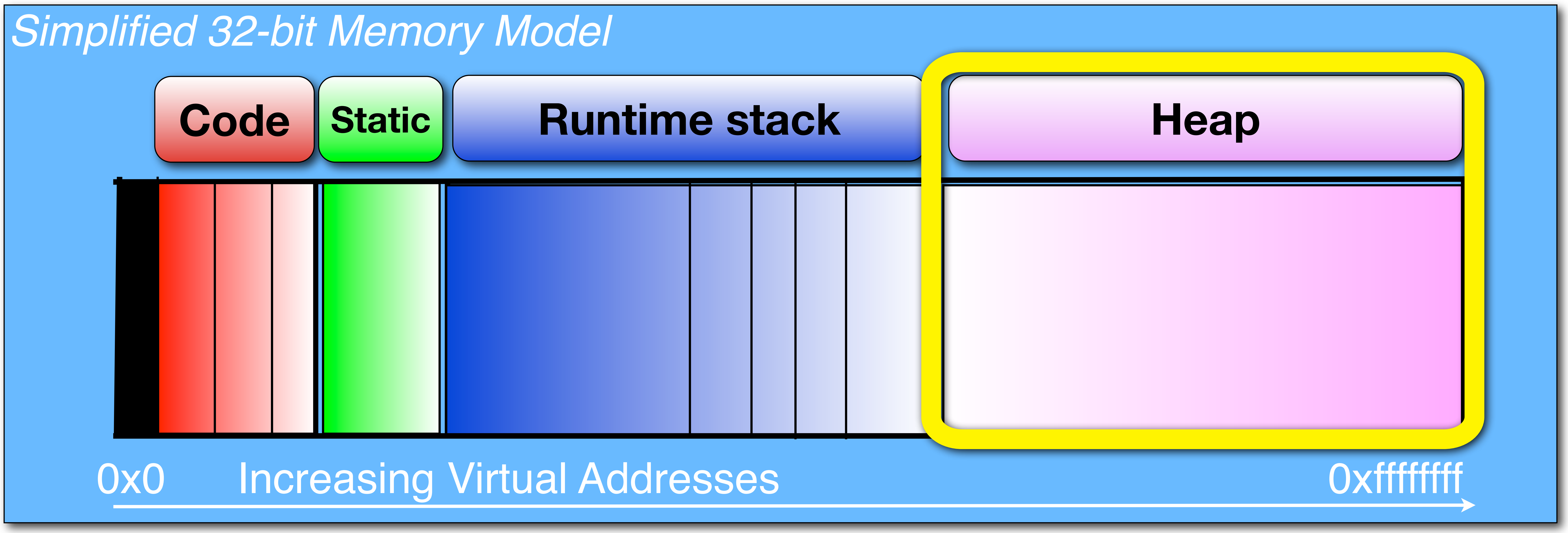
Our Focus

- We'll discuss three RTS components.
  - Garbage collection.
  - Just-in-Time Compilation.
  - Security issues.

Heap Management

Allocation and deallocation of objects on the heap.

- ➡ **Arbitrary** object lifetime.
- ➡ Traditional language design:
  - Code, static, and runtime stack managed by compiler / interpreter.
  - Heap managed by programmer.



Garbage

Memory reclamation.

- An object is “**garbage**” if it is not going to be used again.
- Memory holding garbage **must be reclaimed** in long-running programs.

Classic imperative approach: explicit heap management.

- malloc/free, new/delete, etc.
- Problems: **dangling pointers**, **memory leaks**…
- Experience suggests that programmers, on average, are not very good at correctly identifying garbage.

Garbage Collection

Automatic heap management.

- ➡ The RTS should manage memory, not the programmer.
- ➡ First developed for **Lisp** in 1958
- ➡ Merits hotly contested until ‘90ies.

Widespread use.

- ➡ Essential in **functional languages**
  - e.g., Haskell, ML.
- ➡ Key feature of **scripting languages**
  - e.g., Python, Perl.
- ➡ **Increasingly popular** modern imperative languages
  - e.g, Java, C#.

Reachable Objects

Root Set
The set of objects that are immediately available to a program without following any pointers/references.

Object graph.

- ➡Allocated objects form a **graph**.
  - Vertices: objects.
  - Edges: references/pointers.
- ➡Any non-garbage object must be **reachable** from the **root set**.

Garbage Collection: Techniques

Detecting garbage.

- ➡When is an object no longer being referenced?
- ➡False positives: **program crash**.
- ➡False negatives: **memory leak**.

Garbage collection techniques.

- ➡Reference counting.
- ➡Mark-and-sweep collection.
- ➡Store-and-copy.
- ➡Generational collection.

Reference Counting

Indirect reachability.

- ➡ Each object has an **associated reference counter**.
- ➡ Object graph: how many incoming edges?

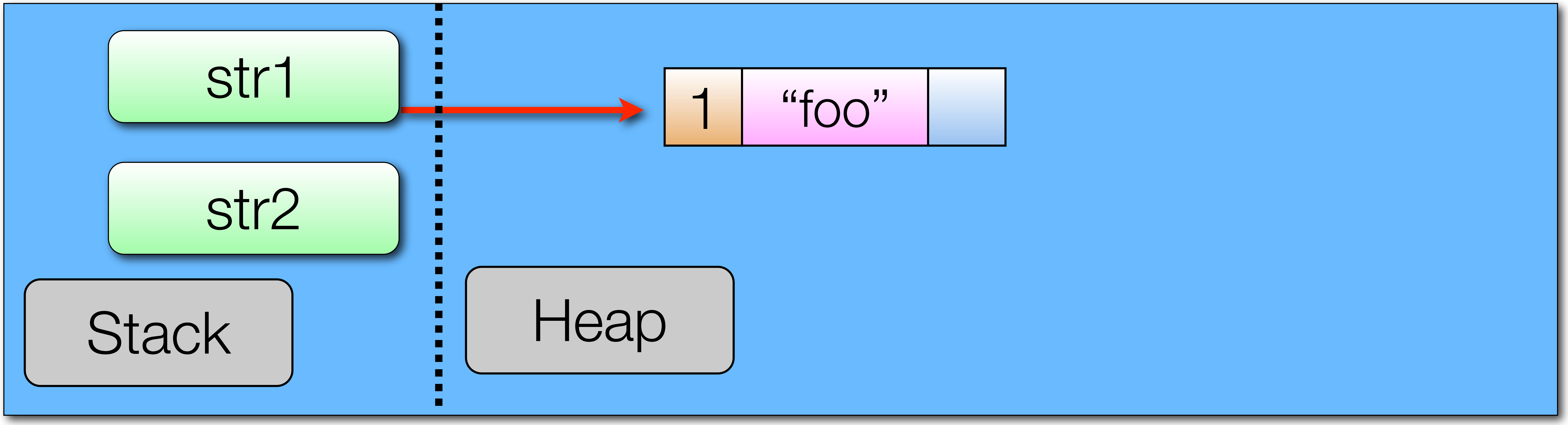
Maintained invariant.

- ➡ Counter is incremented when a new reference is acquired.
- ➡ Counter is decremented when a reference is removed.
- ➡ **If** an object is reachable, **then** its associated reference counter is positive.

Widespread use.

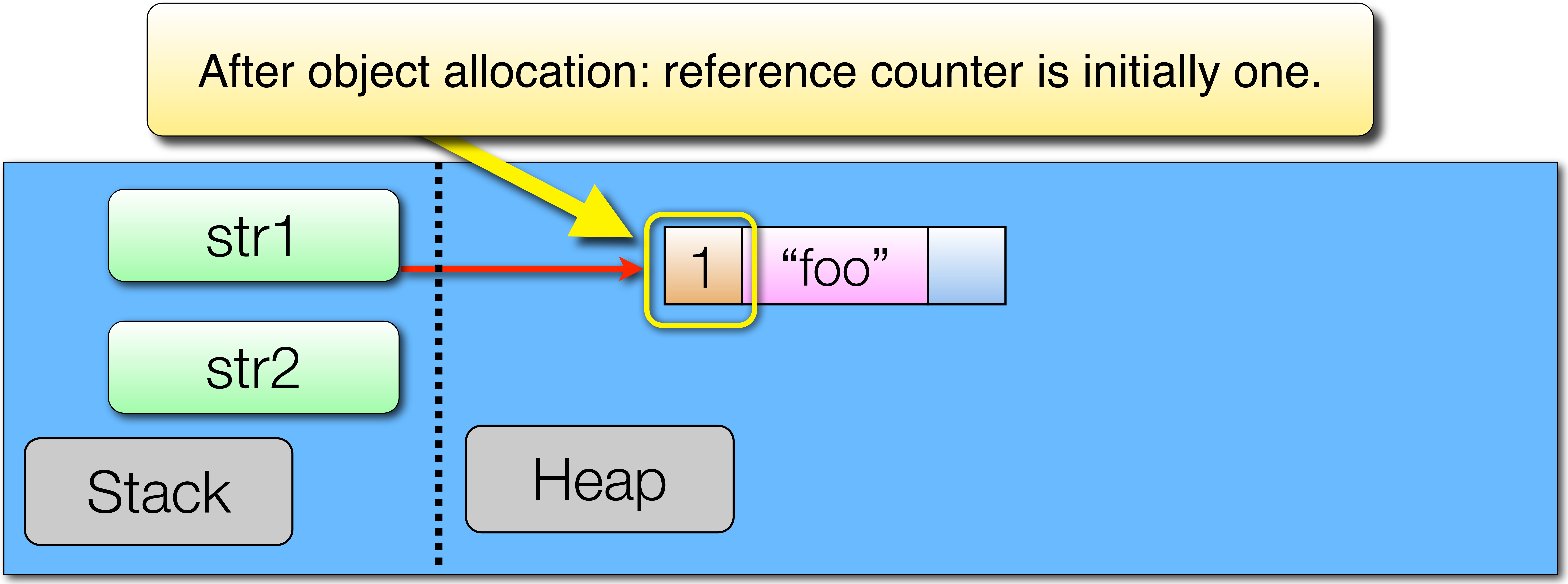
- ➡ Easy to implement in C (but error-prone).
- ➡ Used in Linux kernel, Python, many other projects.

Reference Counting Example



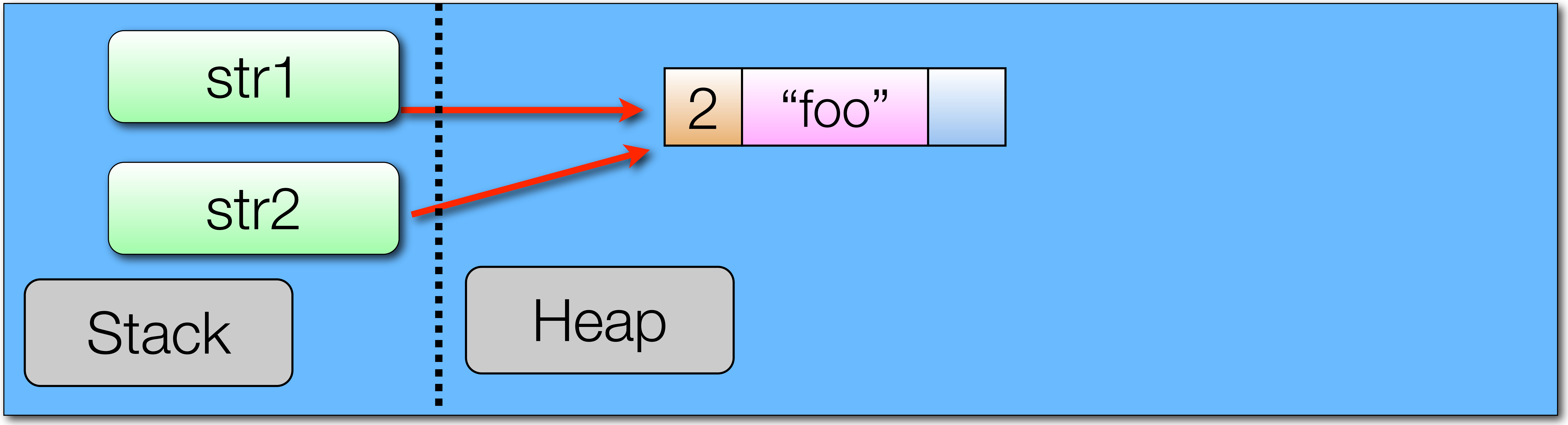

```
str1 = "foo"
```

Reference Counting Example



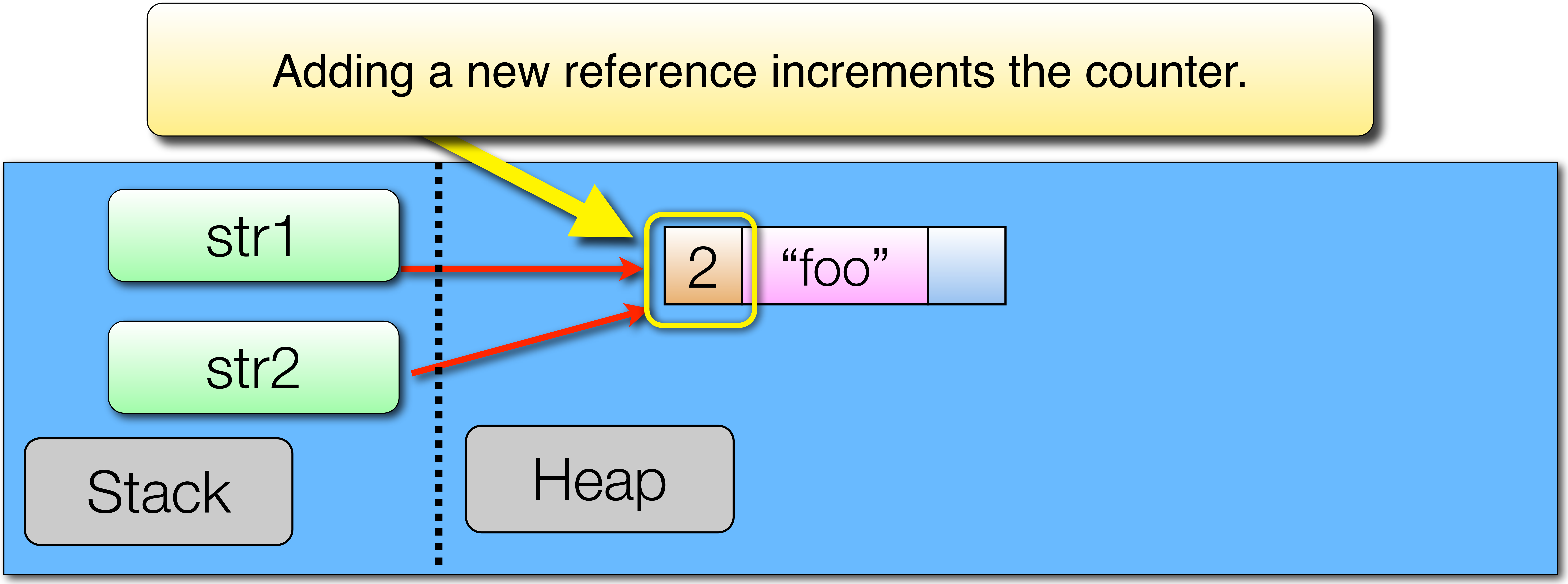
`str1 = "foo"`

Reference Counting Example




```
str2 = str1
```

Reference Counting Example

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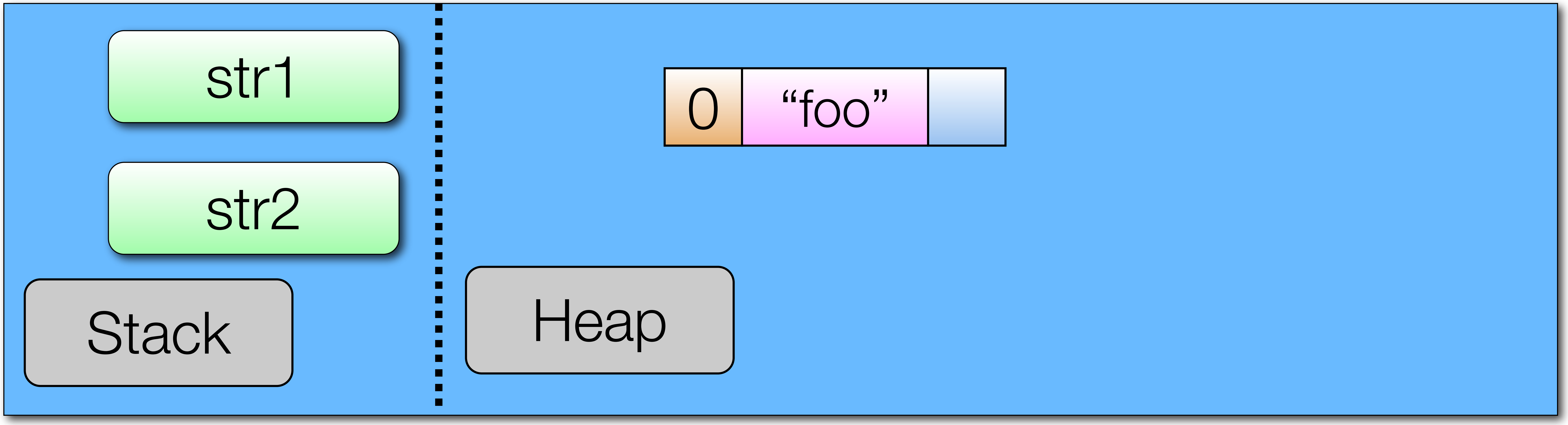
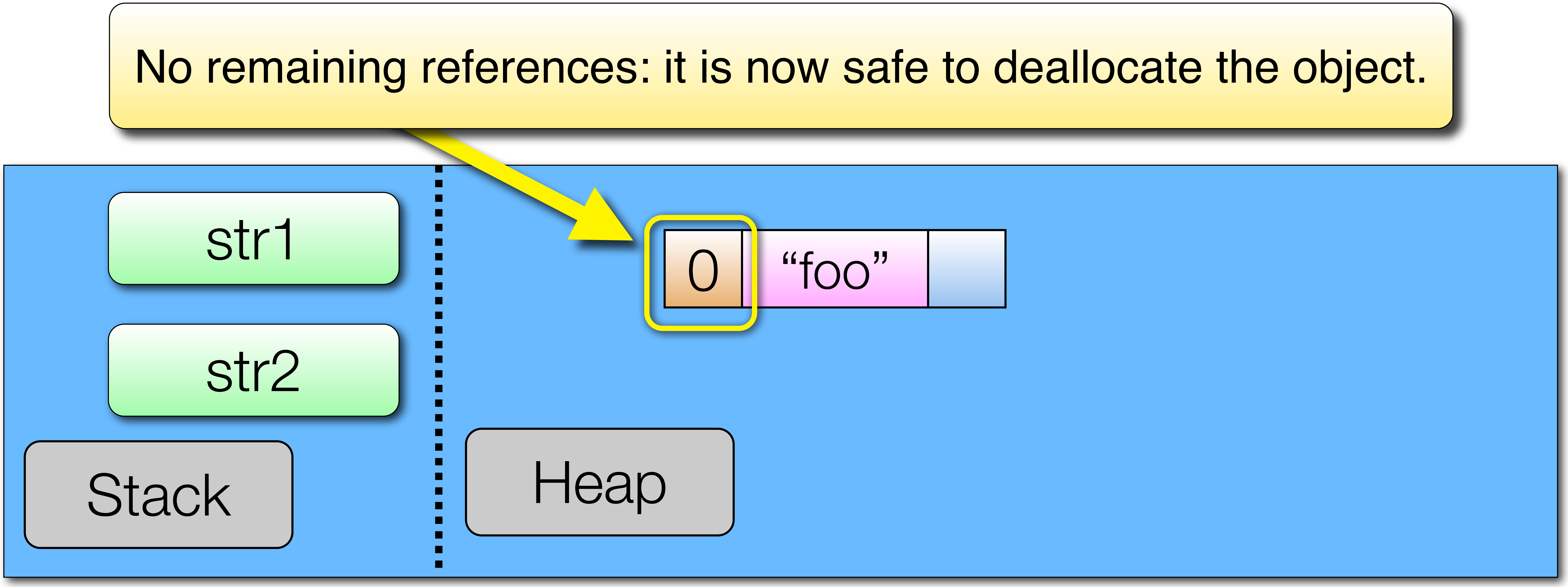
Reference Counting Example




```
str1 = None
str2 = None
```

Reference Counting Example




```
str1 = None
str2 = None
```

Reference Counting: Problems

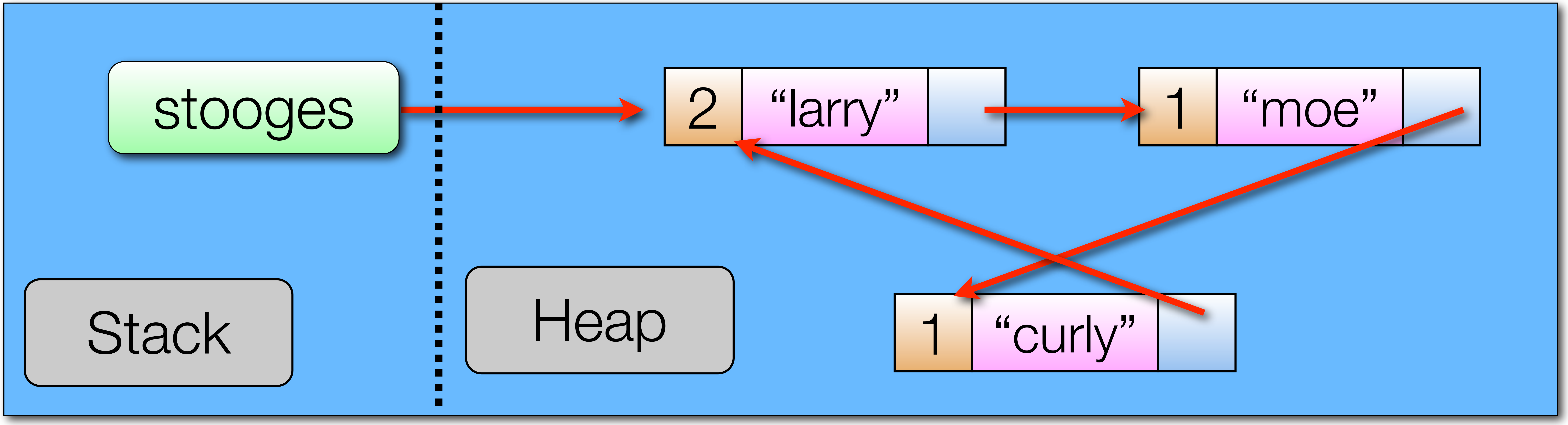
Efficiency.

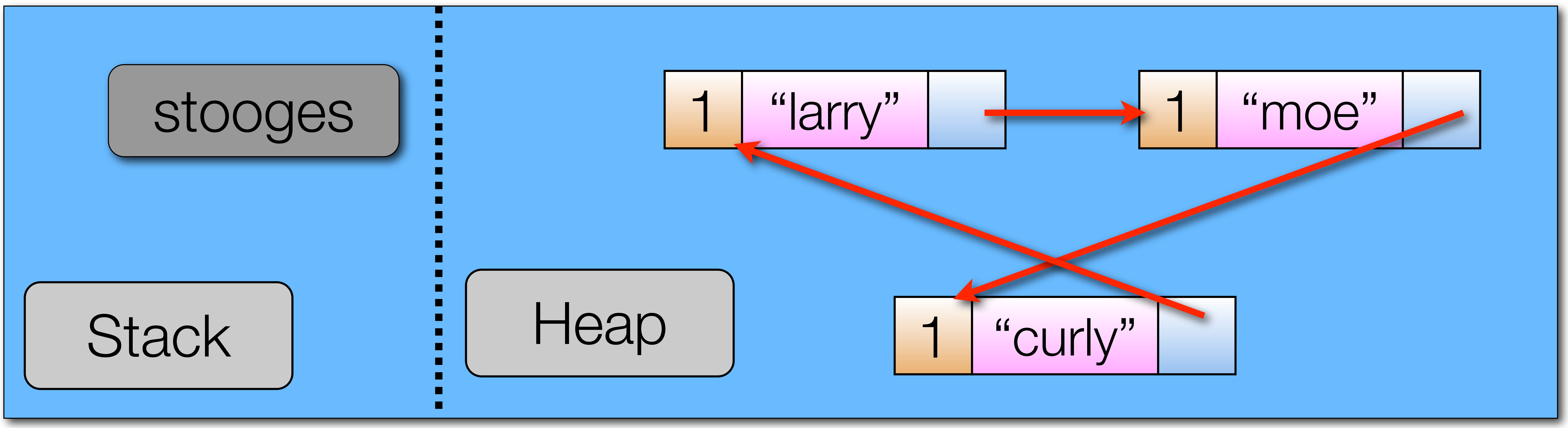
- ➡**Increases number** of (slow) **writes**.
- ➡With multithreading, it may require (even slower) **atomic updates**.

Accuracy.

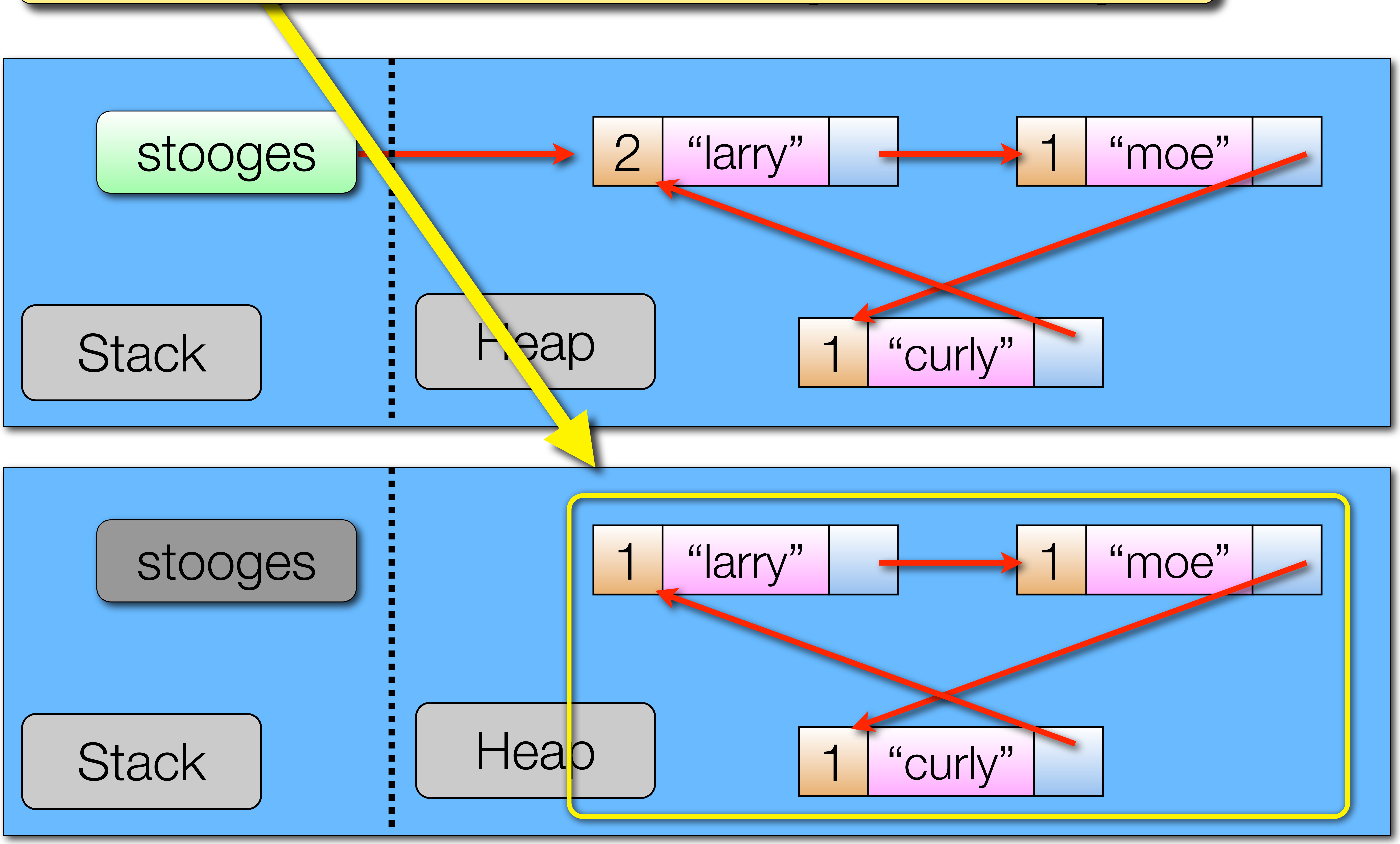
- ➡**Disjoint union types**: what if one variant contains a reference, and another doesn't?
  - ‣Reference counting must track variant tags.
- ➡In a weakly typed language such as C?
  - ‣Cannot reliably tell **pointers** from **integers** apart.
- ➡Cannot detect **circular** garbage.

Cycles in the Object Graph





Memory leak: not reachable, but will not be deallocated.



Mark and Sweep GC

Direct reachability.

- ➡ Instead of using a counter to track **possible** incoming paths, actually **discover all paths** at runtime by **traversing the object graph**.
- ➡ Anything not visited must be garbage.
- ➡ Every objects carries an “in-use” flag.

Algorithm concept.

- ➡ Mark every object in the heap as unreachable by clearing all “in-use” flag.
- ➡ Starting from the root set, traverse all references.
- ➡ **Mark every visited object as reachable** by setting its flag.
- ➡ Reclaim all unused objects (“sweep”).
- ➡ Run when memory is “low”.

Mark and Sweep: Challenges

"Stop the world" GC.

- ➡What if object graph is changed during traversal?
- ➡Simple solution: **program execution is halted** during GC.
  - ‣Can cause noticeable pauses.

Mark and Sweep: Challenges

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Concurrent Garbage Collector:
GC and program can run concurrently (i.e., any interleaving is acceptable).

Incremental Garbage Collector:
GC does not process whole object graph at once. Instead, it is invoked more frequently.

Mark and Sweep: Challenges

Identifying objects.

- ➡How to **identify objects** in the heap?
  - Must carry **size/type tags**, or have uniform size.
  - Alternative: allocate objects of **equal size/type** from specific address ranges.
    - Sometimes called "Big Bag of Pages" (BIBOP).
- ➡How to **discern arbitrary values from pointers**?
  - Could have a number that "points" to a garbage object.
  - Could have a number that "points" outside of heap bounds.

Mark and Sweep: Challenges

Identifying objects.

➡ How t
- Must
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➡ How t
- Coul … ject.
- Coul … bounds.

Precise Garbage Collector:
GC can unambiguously determine whether a given value is a pointer/reference.

Conservative Garbage Collector:
works without discerning pointers/reference from other values with certainty.

Mark and Sweep: Challenges

Memory requirements.

➡GC algorithm runs when **memory is scarce**.

➡**Graph traversal requires memory** itself!

- Proportional to the **longest path** in the object graph.
- Reserves are wasteful…

Tradeoff.

➡Implementation **complexity** vs. **efficiency**.

➡Could use incremental GC to reduce problem.

➡Specialized stack-less techniques exist.

Mark&Sweep vs. Ref. Counting

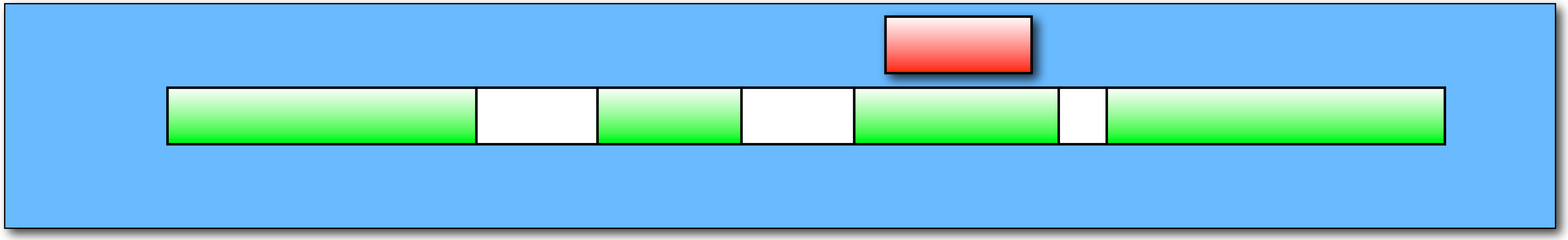
Reference counting.

- ➡Occurs continuously: **no pauses**.
  - ‣But: **overheads are incurred continuously**, too.
- ➡**Leaks** circular structures.
- ➡Relatively **easy to implement**.

Mark & Sweep.

- ➡Difficult to implement efficiently.
  - ‣Esp. avoiding "**stop the world**".
- ➡Pauses, but otherwise **fast execution and allocation**.
- ➡With **precise** GC, no leaking of unreachable objects.

Copying Garbage Collection



simply identifying and freeing garbage doesn't solve fragmentation

Partitioned heap.

- Two **arenas**: live objects arena and free space.
- Allocate from live object area until full.
- Then mark&sweep to find all live objects.
- Copy all live objects to free space.
  - **Fast consecutive allocation**.
- Switch roles: formerly live arena is now free.

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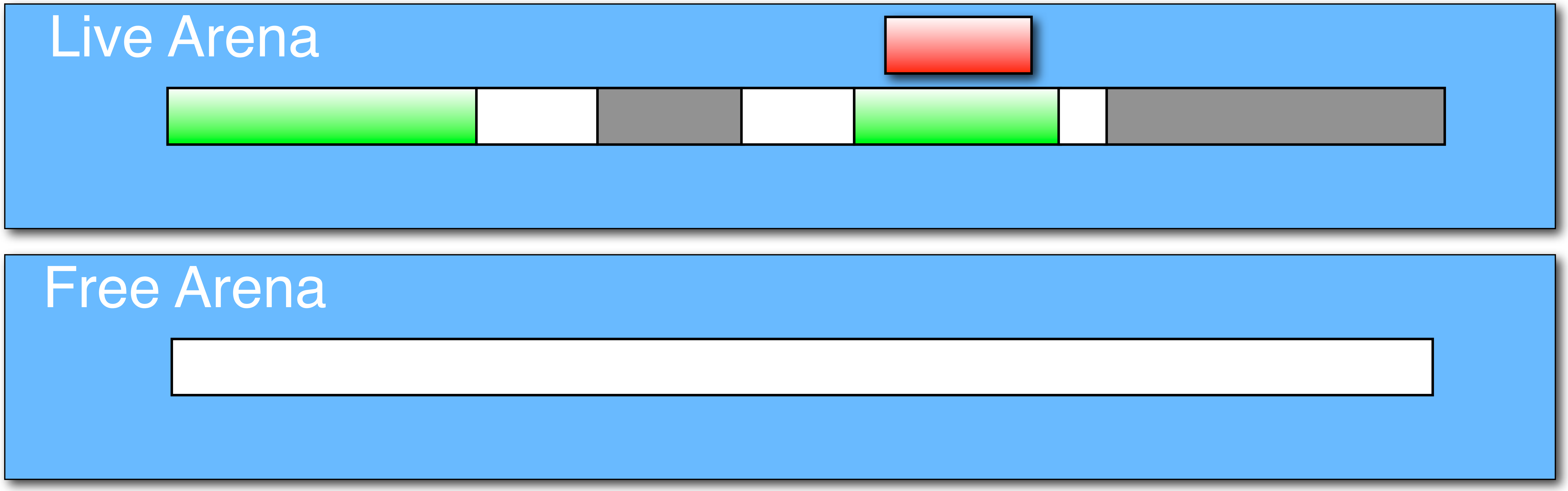

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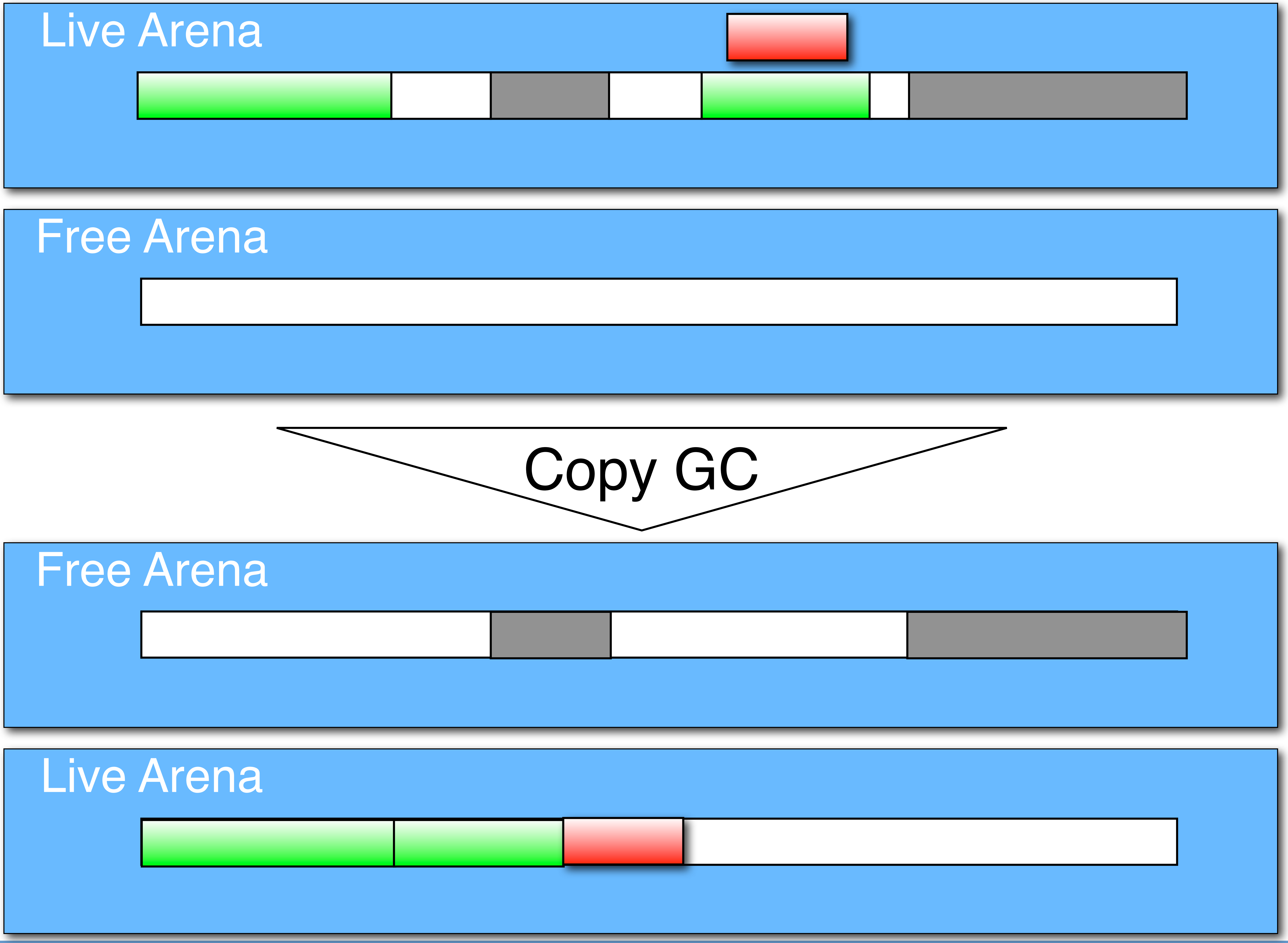

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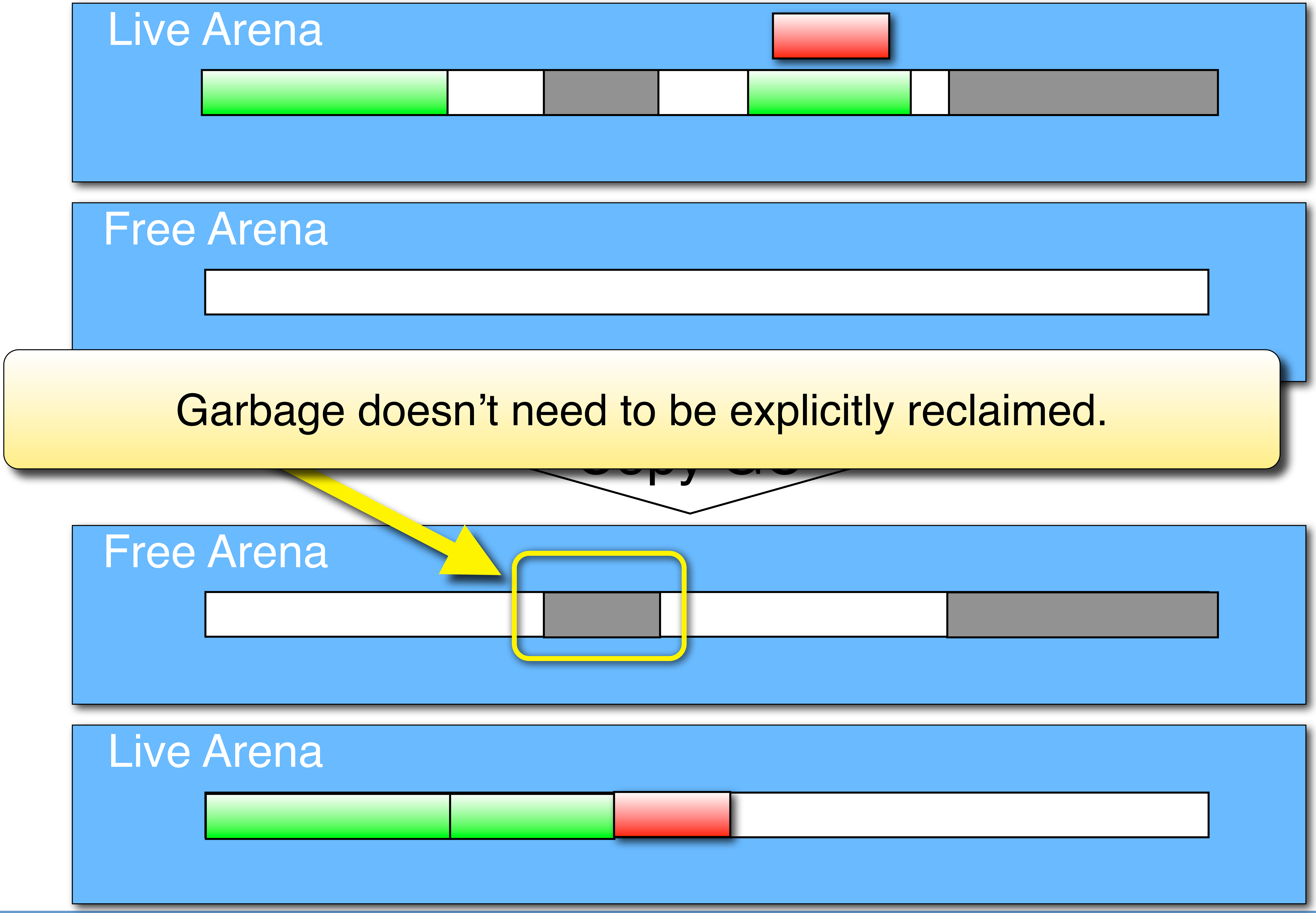

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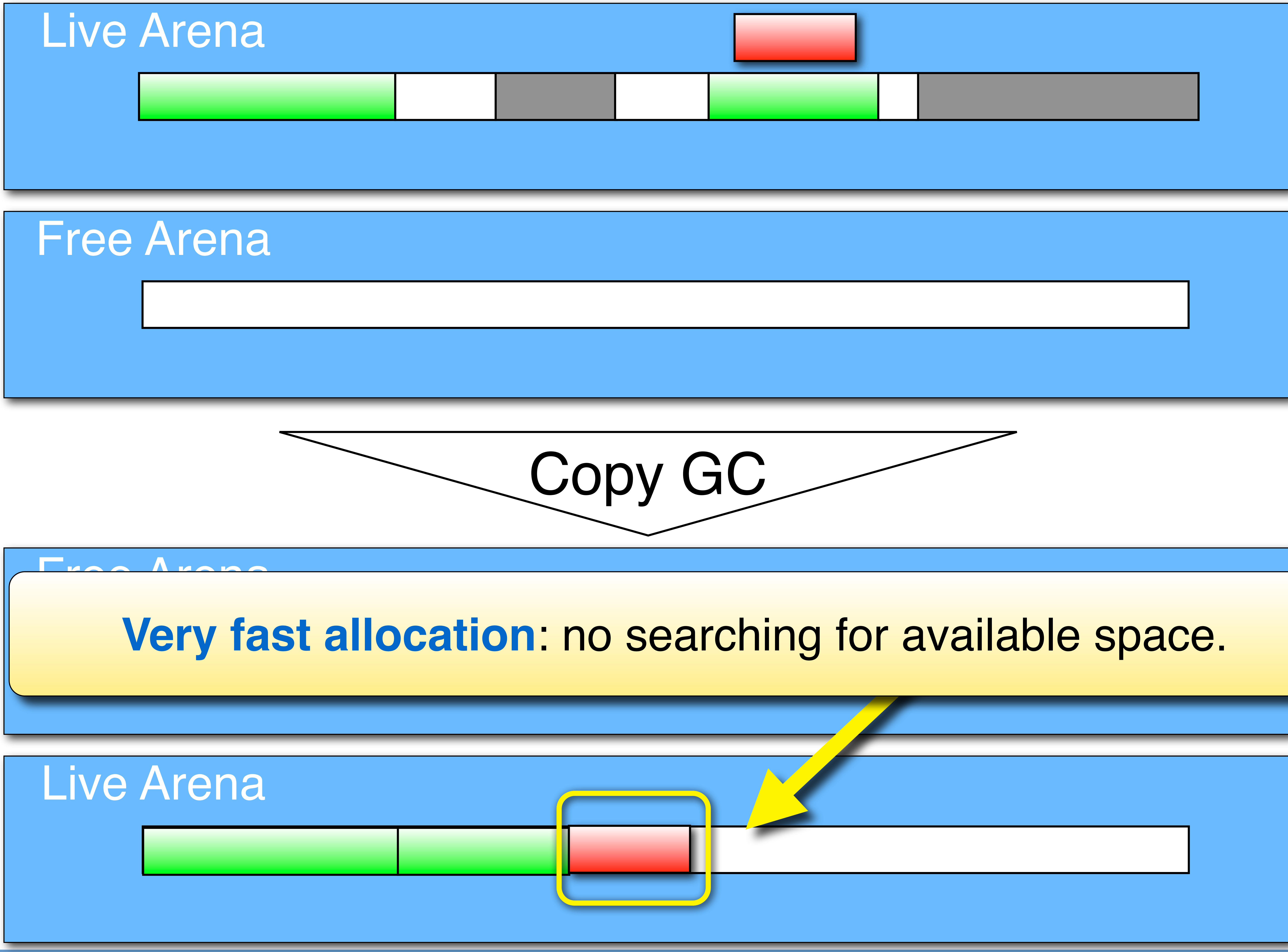
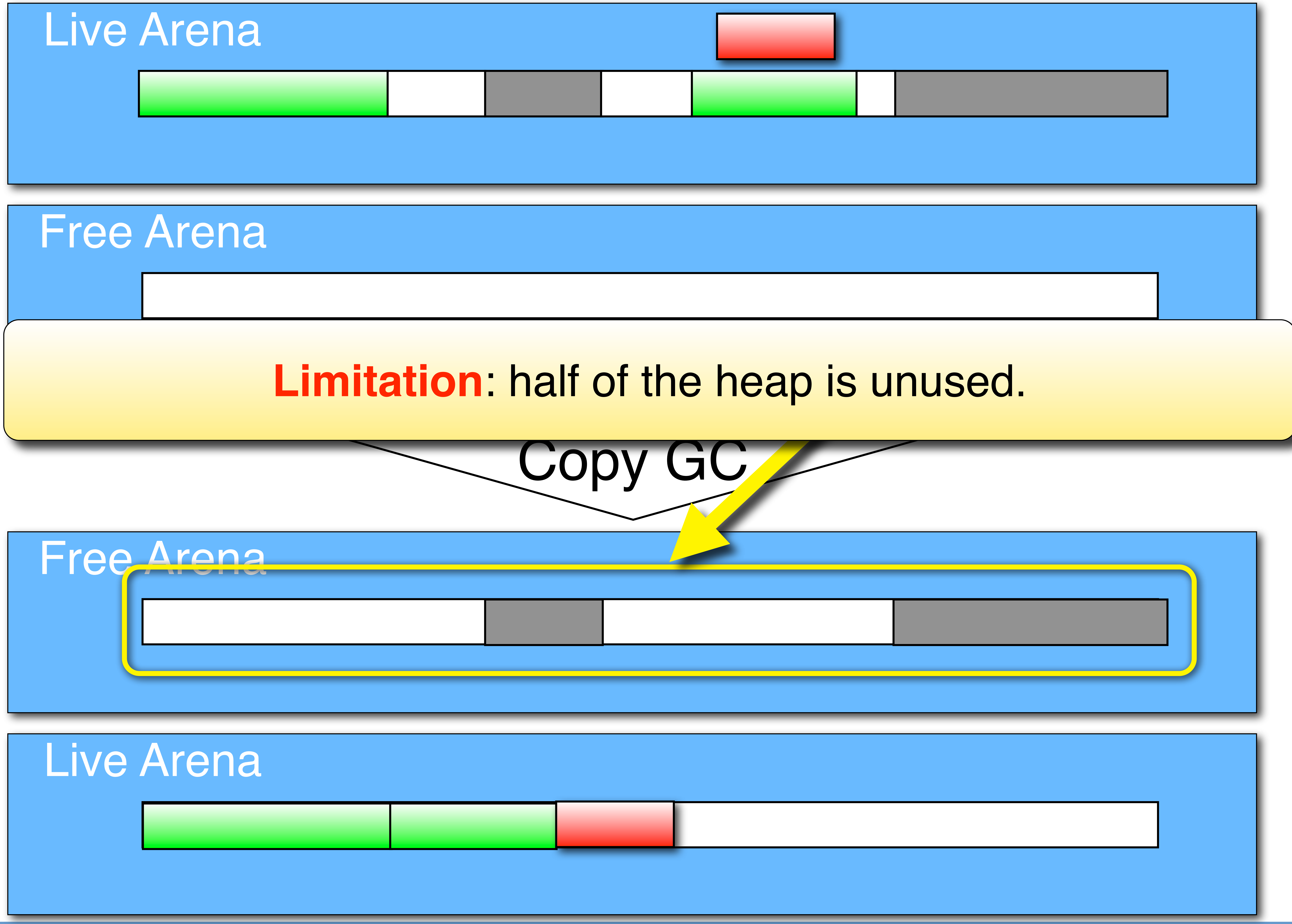


Very fast allocation: no searching for available space.

Copying Garbage Collection



Thursday, April 22, 2010

Generational GC

Generational Hyothesis.

- In many programs there is high "**infant mortality**."
- Most objects are short-lived: they become garbage quickly after allocation.
- Thus, **"older" objects are less likely to become garbage**.

Arenas for different "ages".

- Multiple allocation arenas.
- The "generation 0 arena" (the "**nursery**") is used for new allocations.
- **"Survivors" are copied to the next arena**.
- Which is also gc'ed at some point, at which generation 1 objects move to the generation 2 arena, etc.

Generational GC

Generational Hyothesis.

➡ In many programs there is high "**infant mortality**."

Objects that are unlikely to be garbage are only examined infrequently: **reduced GC runtime**.

New objects can be allocated very cheaply from the nursery (simply increment the "end of last object" pointer).

Modern high-performance VMs often use this approach (e.g., Java Virtual Machine).

GC vs. Manual Deallocation

Efficiency.

- ➡**Correct** manual heap management is more efficient than naive GC.
- ➡But software development cost considerations strongly favor GC.
- ➡**GC can be faster than manual management** due to reduced allocation costs (copying GC).

Finalizers and non-memory resources.

- ➡Languages such as Java use finalizers to free **non-memory resources** (such as file handles) when an object is freed.
- ➡**Problem**: may run out of non-memory resources before GC kicks in.

Just-in-Time Compilation (JIT)

Static compilation.

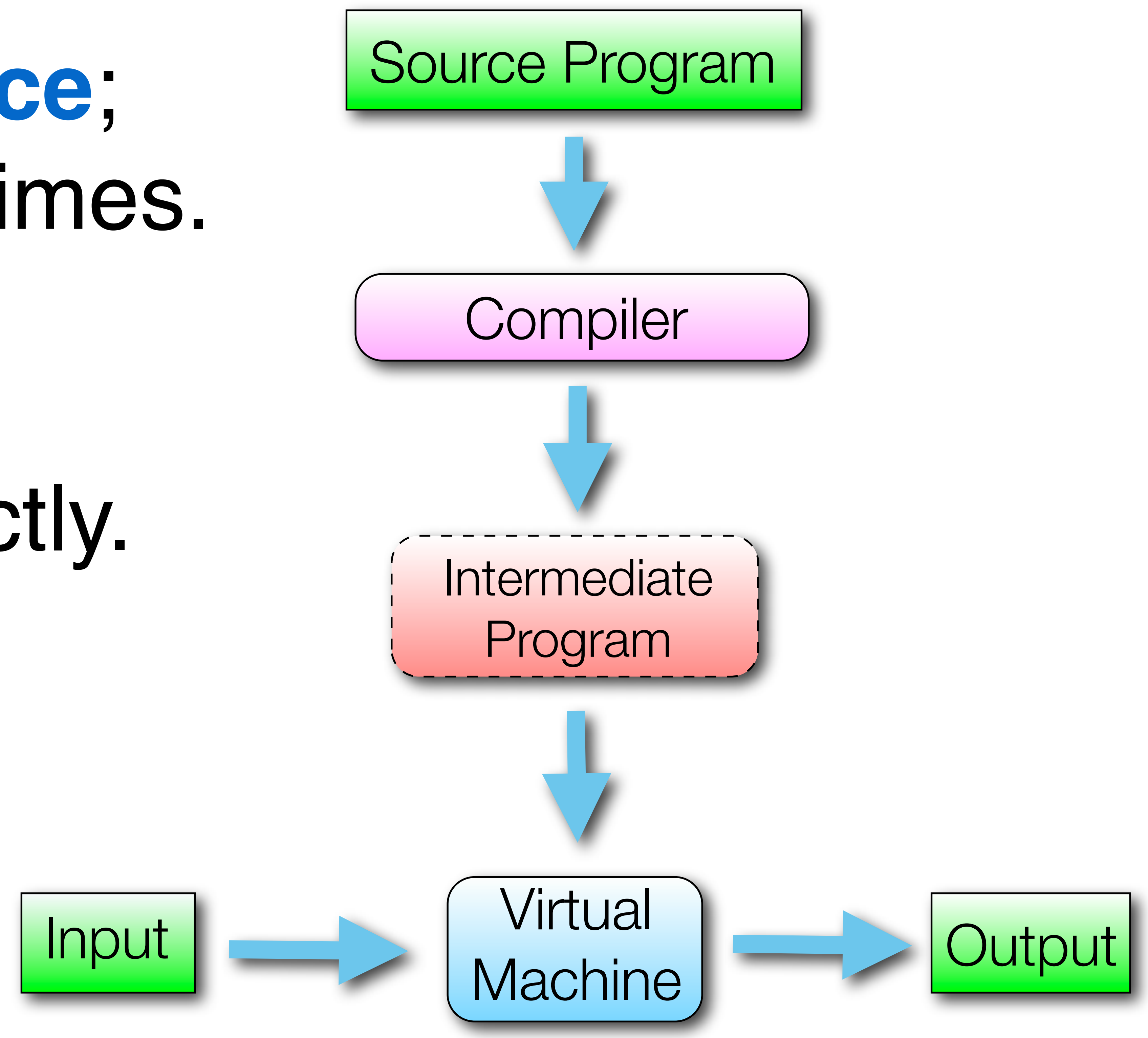
- ➡Compile time vs. run time.
- ➡Compiler produces machine code **once**; resulting program is executed many times.

Pure interpretation.

- ➡interpreter evaluates syntax tree directly.
- ➡**Slow**.

Bytecode interpretation.

- ➡Source compiled to bytecode.
- ➡**Bytecode interpreted by VM**.
- ➡Still **slower** than statically compiled programs.



Just-in-Time Compilation (JIT)

JIT: compile byte code at run time to **speed up** overall program execution.

➡Compiler produces machine code **once**; resulting program is executed many times.

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- ➡**Slow**.

Sometimes referred to as **ahead-of-time compilation** (**AOT**).

- ➡**Bytecode interpreted by VM**.
- ➡Still **slower** than statically compiled programs.

Idea and Limitations

"Write once, run anywhere."

- ➡ Combine **efficiency of compilation** with **flexibility of interpretation**.
- ➡ "Late binding of machine code."
- ➡ Java: web applets, **mobile phones**, embedded systems…

Overheads.

- ➡ **Startup delay**.
  - After a program starts, parts must be compiled before output is produced, which can result in a noticeable delay.
  - Hide by running interpreter and JIT compiler **in parallel**.
  - Avoid compiling whole program at once.

JIT Overhead

Piecewise compilation.

- Program is compiled **on demand** in small chunks.
- Subroutine at a time, maybe even only **parts of a subroutine**.

Tradeoff.

- **Compilation takes considerable time**…
- **…but compiled code is faster**.
- Thus: compiled code must be **executed many times** to make tradeoff beneficial.

Threshold.

- Practical JIT systems trigger compilation only for code fragments that are executed more often then some **threshold** (e.g., 100 times).
- Intuition: focus on the **common paths**.
  - avoid initialization code and rare error paths
  - optimize main work loops

JIT Overhead

Piecewise compilation

outine.

The exact threshold depends on the **efficiency of the byte code interpreter** and the **JIT compilation speed** and must be **determined experimentally**.

- ➡ **…but compiled code is faster.**
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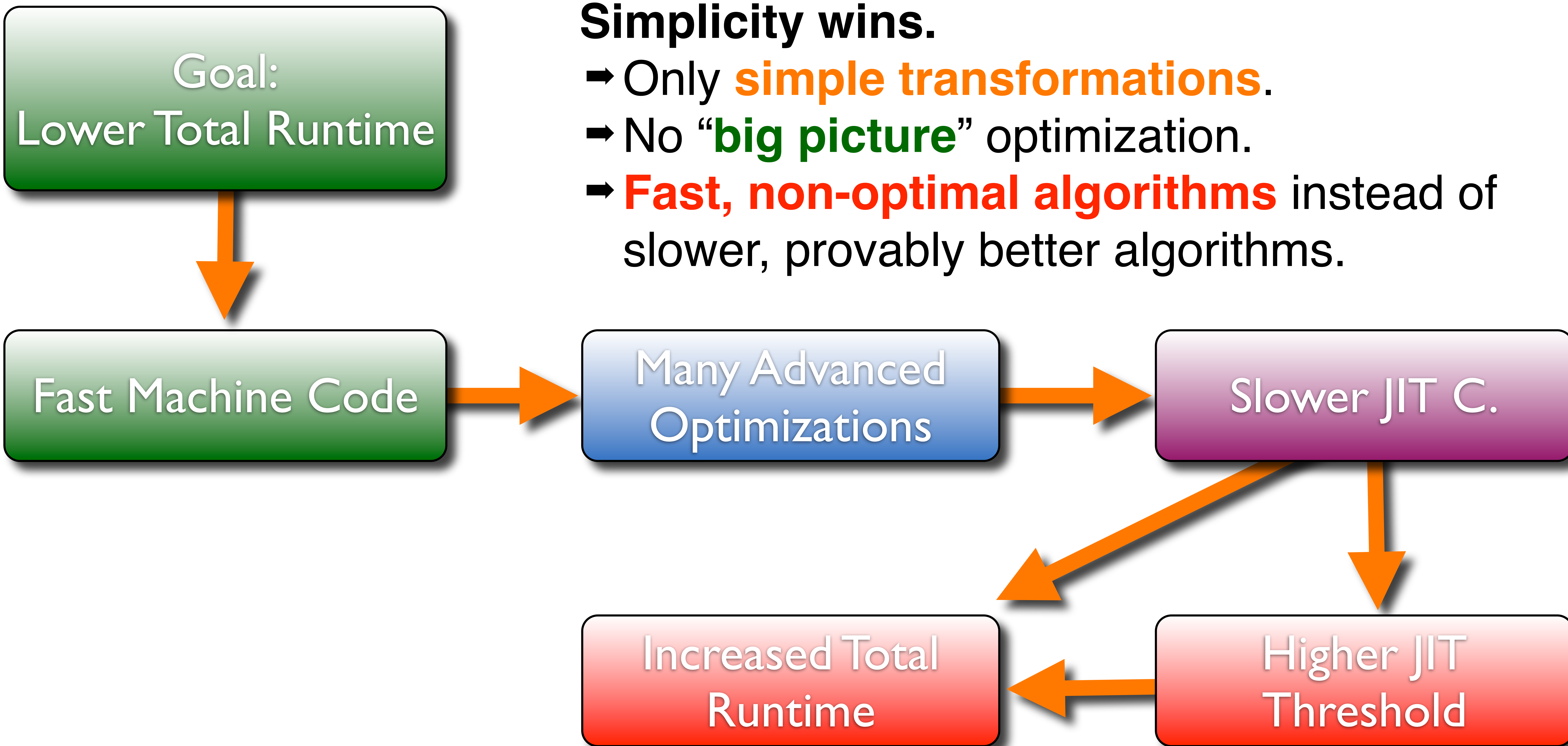
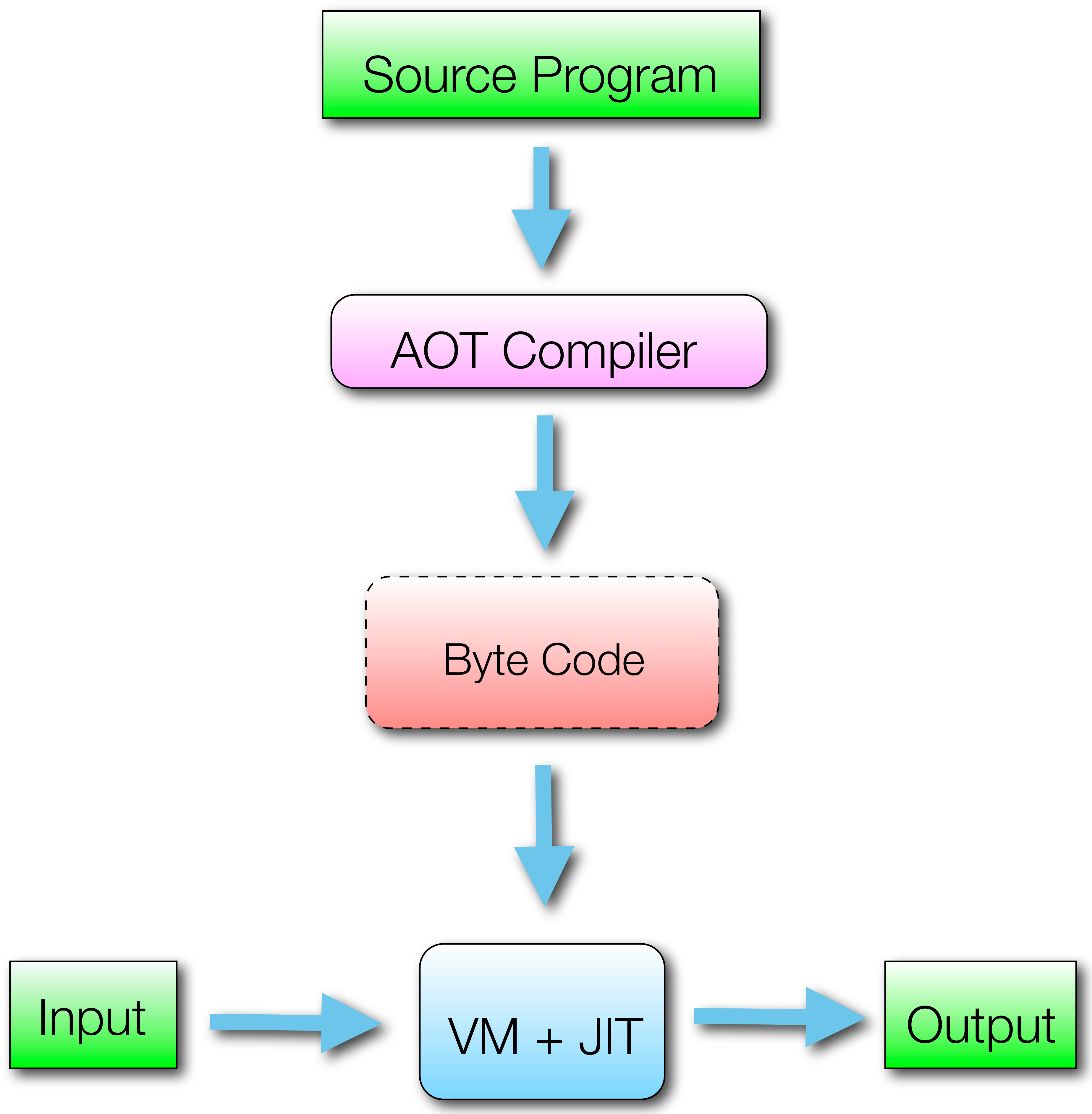
Optimization vs. JIT Compilation

Simplicity wins.

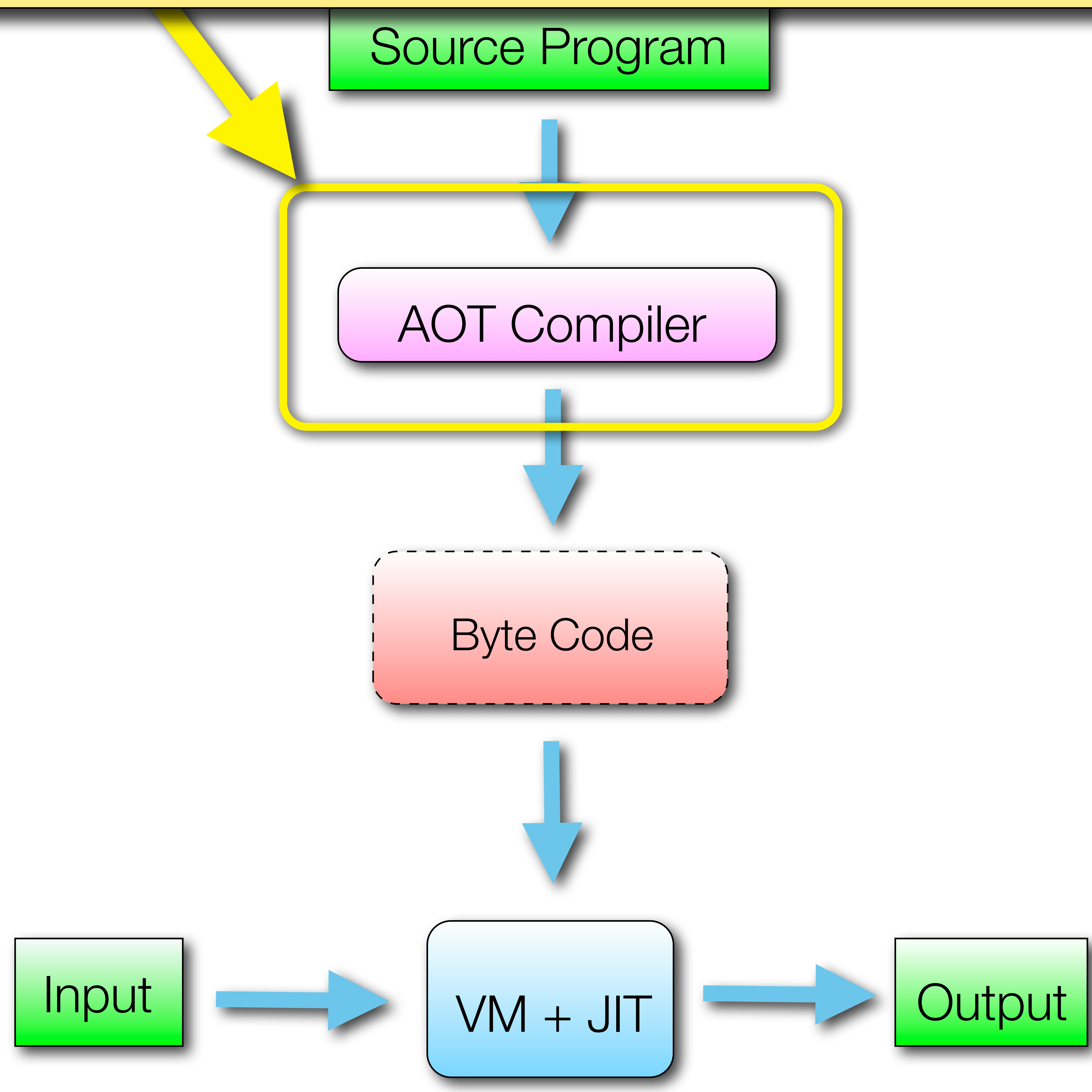
- ➡ Only **simple transformations**.
- ➡ No "**big picture**" optimization.
- ➡ **Fast, non-optimal algorithms** instead of slower, provably better algorithms.



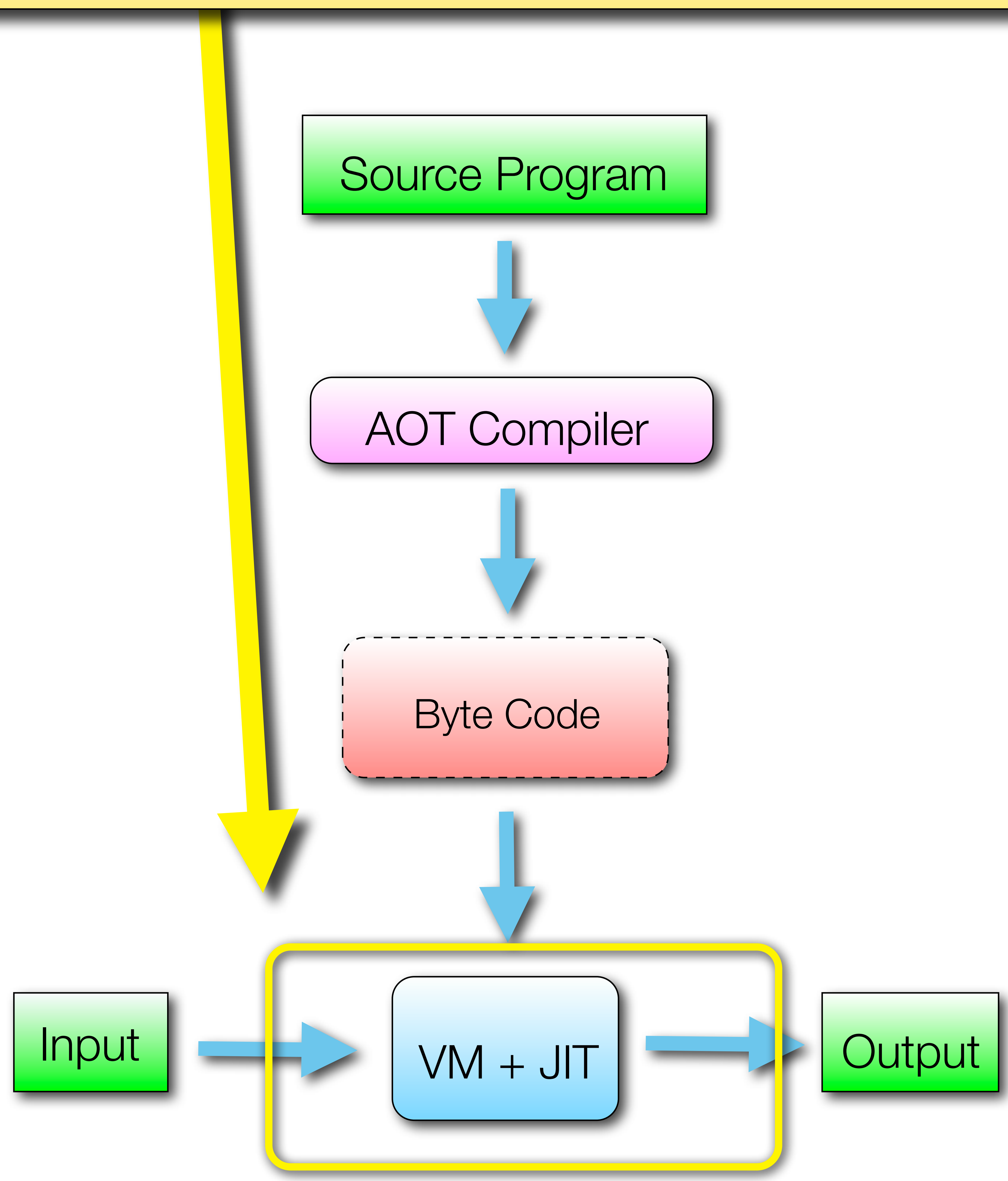
Optimizations



The "heavy lifting":
intra-procedural analysis, common sub-expression analysis, dead code eliminations, flow analysis, polymorphism, etc.



Simple transformations:
basic byte code blocks to equivalent machine code.



JIT Advantages

Trace collection.

- ➡Record execution statistics during interpretation.
- ➡Can (re-)optimize at run time.

JIT can outperform AOT.

- ➡**Additional information** available at run time.
  - ‣**Specific types** (instead of interfaces), accurate branch prediction.
- ➡Can be used to **generate specialized code**.
  - ‣E.g., suppress error checking that is not needed for a **particular data set**.
- ➡Additional **inlining** possibilities.

JIT Advantages

Trace collection.

- ➡Record execution statistics during interpretation.
- ➡Can (re-)optimize at run time

Tradeoff: long-running vs. short-running processes

Example: Java VM has a server mode that does spends more time on aggressive optimizations.

branch prediction.

- ➡Can be used to **generate specialized code**.
  - ‣E.g., suppress error checking that is not needed for a **particular data set**.
- ➡Additional **inlining** possibilities.

JIT and Prototype-Based Languages

Challenges.

- Java: JIT on class methods.
- **What if there are no classes?**

Tracing JIT.

- Derive "**implicit**" **classes** based on source code location where object was created (i.e., where the prototype was assigned).
- Most **prototypes are not changed during run time**.
- Must re-JIT an object if either
  - the object's **prototype is changed**, or
  - a **new prototype** is assigned.

Binary Translation / Binary Rewriting

Compiling machine code to machine code.

- ➡Either AOT or JIT.
- ➡Basically a **compiler without source code**.

Uses.

- ➡Debugging, logging (add invariant checking, etc.).
- ➡**Performance analysis**.
- ➡Adding security hooks.
  - ‣Or **exploits**…
- ➡**Legacy system emulation**.
  - ‣E.g.: Apple's **Rosetta**.

Security Issues

Untrusted code.

- Third party code that might be malicious.
- Often downloaded automatically via Internet.
  - **Embedded Javascript**, Java applets, Flash, etc.
  - Browser plugins.

Byte code validation.

- Proving **arbitrary properties** of arbitrary source code is impossible.
  - Halting problem…
- Idea: allow only "known good" byte code.
  - Be conservative.

Alternative.

- **Code signing**: attestation by trusted third party "this is ok."

Security Issues

Untrusted code.

Java Track Record:
Many bugs and thus security vulnerabilities over the years.

- Browser plugins.

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Security Issues

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- Third pa
- Often d
  - **Embed**
  - Browser plugins.

Example:
Microsoft-certified Windows device drivers.

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