# DATA TYPES & MEMORY MANAGEMENT

## PRINCIPLES OF PROGRAMMING LANGUAGES


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Where subroutines allow us to build control abstractions, a language's type system determines the kind of data abstractions we can build.

# ROAD MAP

- Type Systems
- Records
- Arrays
- Associative arrays
- Pointers
- Memory management
- Garbage collection

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# TYPE SYSTEMS

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- Custom operations for built-in and custom types

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- **Type compatibility:** Can a value of a certain type be used in a certain context?
- **Type inference:** How is the type of an expression computed from the types of its parts?

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In some statically typed languages (e.g., ML), the programmer does not specify types at all. They are inferred by the compiler.

# DEFINITION OF TYPES

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**Classification of types:**

- **Denotational:** A type is a set of values.
- **Constructive:** A type is built-in or composite.
- **Abstration-based:** A type is defined by an interface, the set of operations it supports.

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**Composite types:** Records, arrays, files, lists, sets, pointers, …

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A nested record definition in Pascal:

```
type ore = record
  name             : short_string;
  element_yielded : record
    name           : two_chars;
    atomic_n       : integers;
    atomic_weight : real;
    metallic       : Boolean
  end
end;
```

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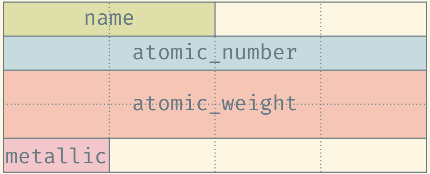
  end
end;
```

Accessing fields:

- `ore.element_yielded.name`
- `name of element_yielded of ore`

# MEMORY LAYOUT OF RECORDS

Aligned (fixed ordering):



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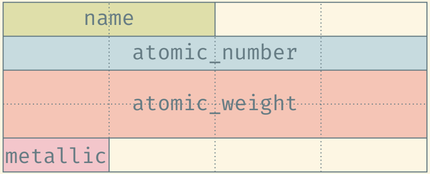


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- + One instruction per element access
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  (Good for systems programming)

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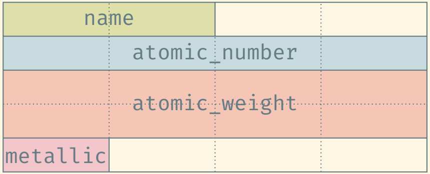


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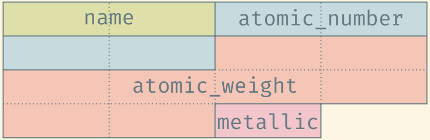


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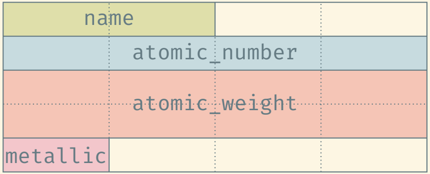


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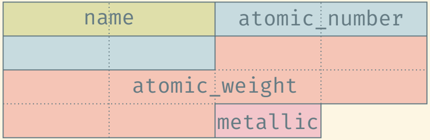


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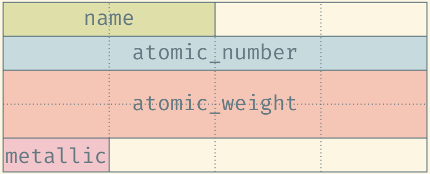


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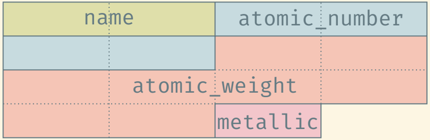


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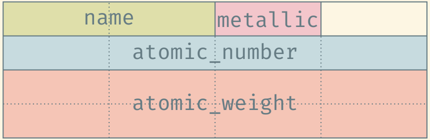


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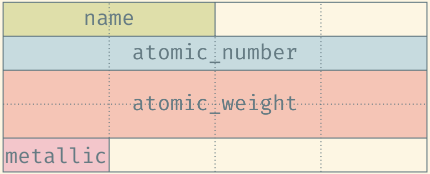


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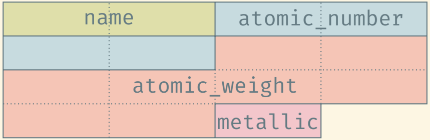


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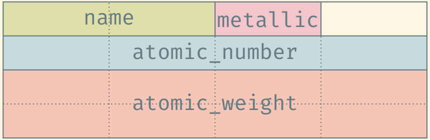


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| Stored where? | Shape fixed when? | | |
|---|---|---|---|
| | Compile time | Elaboration time | Dynamic |
| Static address | Static | — | — |
| Stack | Local | Local | — |
| Heap | Dynamic | Dynamic | Dynamic |

Issues:

- Memory allocation
- Bounds checks
- Index calculations (higher-dimensional arrays)

# ELABORATION-TIME SHAPE BINDING AND DOPE VECTORS


Efficient access to stack-allocated objects is based on every element having a fixed offset in the stack frame.

How can we achieve this when we allow stack-allocated objects (e.g., arrays) to have sizes determined at elaboration time?

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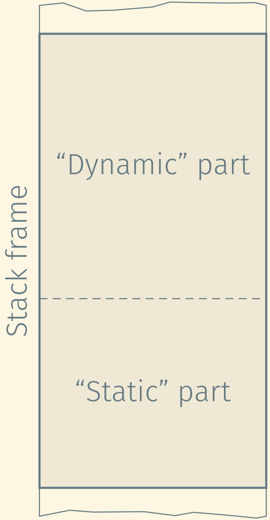


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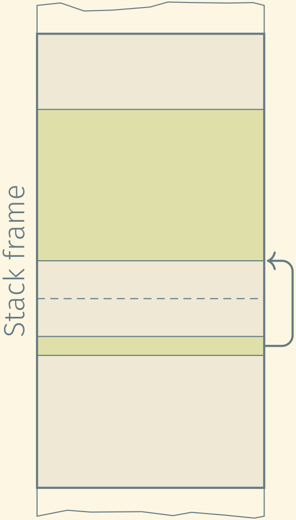


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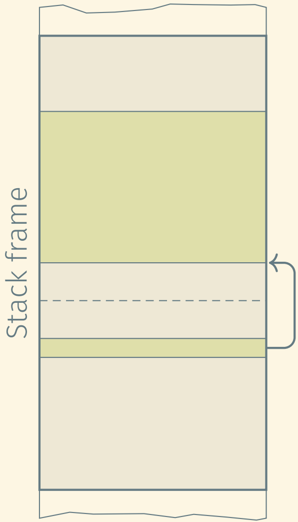


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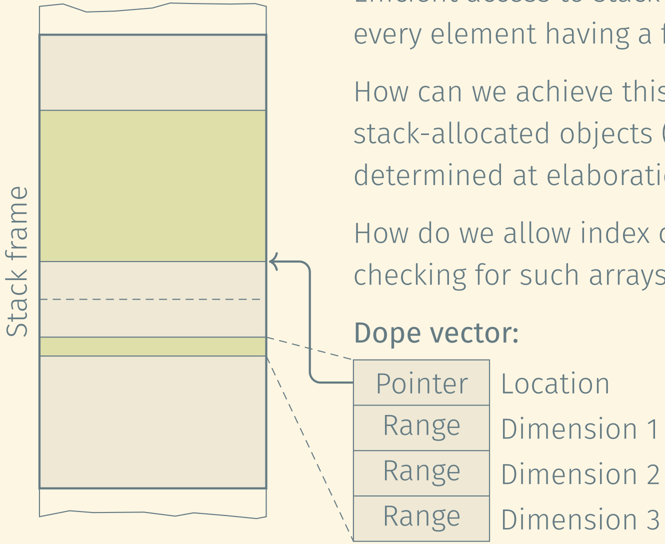


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**Dope vector:**

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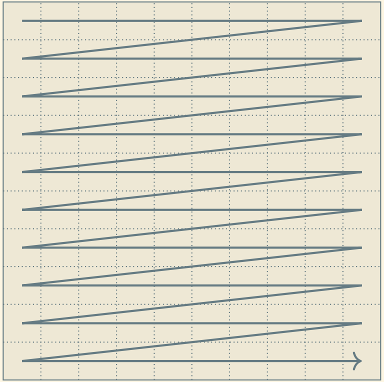

Row-major layout

Column-major layout

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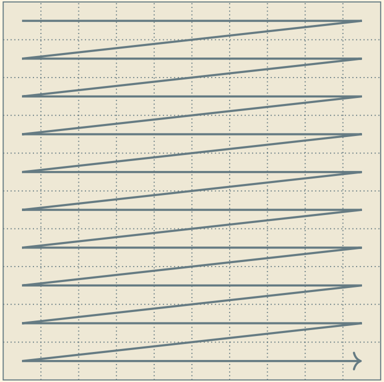

Row-major layout

Column-major layout

There are more sophisticated block-recursive layouts which, combined with the right algorithms, achieve much better cache efficiency than the above.

# CONTIGUOUS VS ROW-POINTER LAYOUT

```
char days[][10] = {
  "Monday", "Tuesday", "Wednesday",
  "Thursday", "Friday", "Saturday",
  "Sunday"
};
days[2][3] == 's';
```

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| M | o | n | d | a | y | \0 | | | |
| T | u | e | s | d | a | y | \0 | | |
| W | e | d | n | e | s | d | a | y | \0 |
| T | h | u | r | s | d | a | y | \0 | |
| F | r | i | d | a | y | \0 | | | |
| S | a | t | u | r | d | a | y | \0 | |
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```

```c
char *days[] = {
  "Monday", "Tuesday", "Wednesday",
  "Thursday", "Friday", "Saturday",
  "Sunday"
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**Example:**
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**Different lookup operations for different notions of equality:**

- `assq` uses `eq?` (identity)
- `assoc` uses `equal?` (same value)
- `assv` uses `eqv?` (halfway in between)

# ARRAYS, LISTS, AND STRINGS

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Strings are arrays of characters in imperative languages and lists of characters in functional languages.

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**Storage reclamation:**

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**Advantages and disadvantages of explicit storage reclamation:**

+ Garbage collection can incur serious run-time overhead.
– Potential for memory leaks.
– Potential for dangling pointers and segmentation faults.

# POINTER ALLOCATION AND DEALLOCATION

C:

- `p = (element *)malloc(sizeof(element))`
- `free(p)`
- Not type-safe, explicit deallocation

Pascal:

- `new(p)`
- `dispose(p)`
- Type-safe, explicit deallocation

Java/C++:

- `p = new element()` (semantics different between Java and C++, how?)
- `delete p` (in C++)
- Type-safe, explicit deallocation in C++, garbage collection in Java

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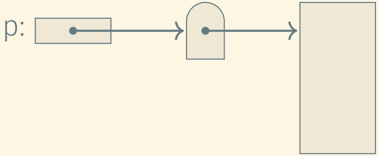
**Techniques to catch them:**

- Tombstones
- Keys and locks

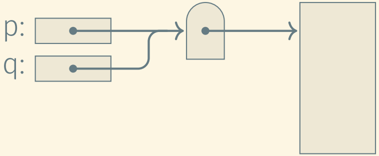
**Idea:** Better crash and expose the bug than do the wrong thing.

# TOMBSTONES (1)

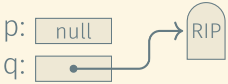
`new(p)`




`q := p`




`delete(p)`



# TOMBSTONES (2)

Issues:

- Space overhead
- Runtime overhead (two cache misses instead of one)
- Check for invalid tombstones = hardware interrupt (cheap):
  - RIP = null pointer
- How to allocate the tombstones?
  - From separate heap (no fragmentation)
  - Need reference count or other garbage collection strategy to determine when I can delete a tombstone.
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**Interesting side effect:**

- The extra level of indirection allows us to compact memory.

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```

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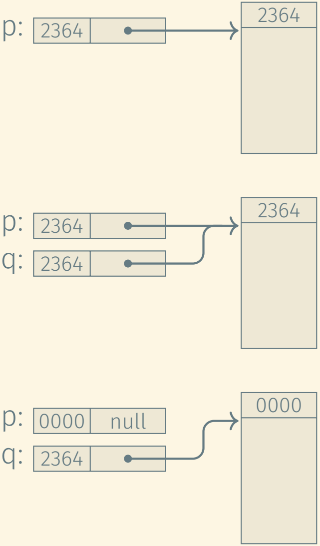

# LOCKS AND KEYS (2)

Comparison to tombstones:

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Languages that provide for such checks for dangling references often allow them to be turned on/off using compile-time flags.

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**Garbage collection**

Automatic reclamation of heap space

- Essential for functional languages
- Popular in modern imperative languages (Java, Python, Ada, Clu, ...)
- Difficult to implement
- Slower than manual reclamation

# GARBAGE COLLECTION STRATEGIES

- Reference counts
- Mark and sweep
- Mark and sweep variants:
  - Stop and copy
  - Generational GC

# REFERENCE COUNTS (1)

```
a = new Obj();
```

```
a = new Obj();
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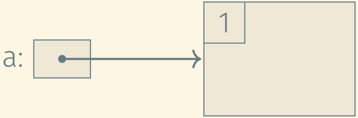

# REFERENCE COUNTS (1)

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b = new Obj();
```
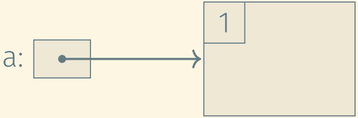
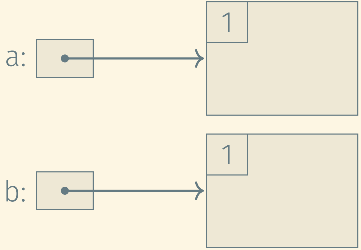
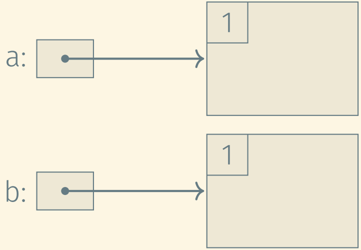



```
a = new Obj();
b = new Obj();
```



# REFERENCE COUNTS (1)

```
a = new Obj();
b = new Obj();
b = a;
```



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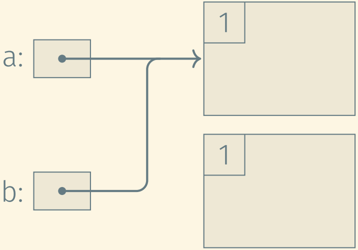

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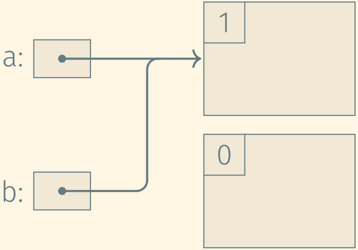

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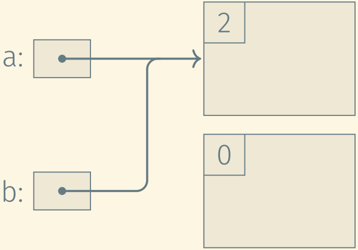

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```
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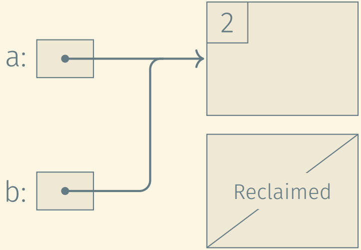
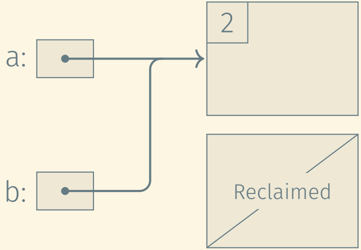


# REFERENCE COUNTS (1)

```
a = new Obj();
b = new Obj();
b = a;
a = null;
```



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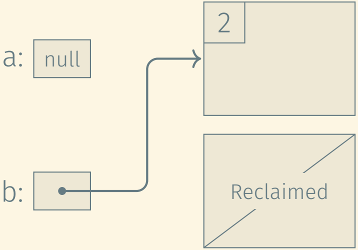

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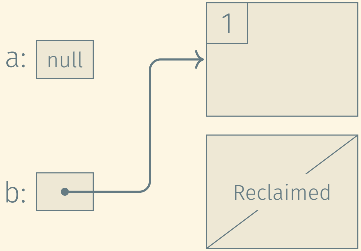

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```
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b = new Obj();
b = a;
a = null;
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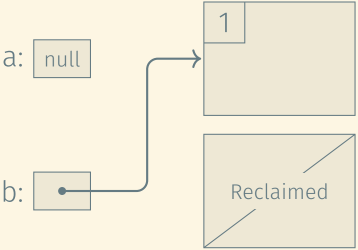

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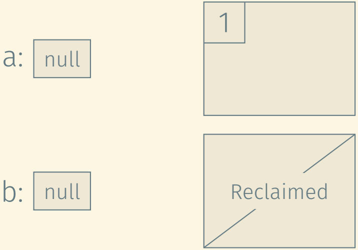

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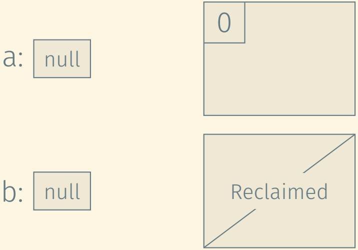

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b = a;
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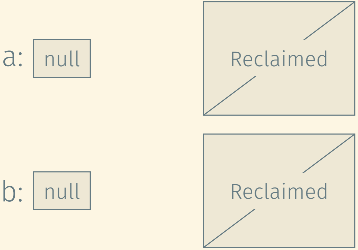


**Subroutine return:**

- Decrease reference counts for all objects referenced by variables in subroutine's stack frame.
- Requires us to keep track of which entries in a stack frame are pointers.

# REFERENCE COUNTS (2)

**Subroutine return:**

- Decrease reference counts for all objects referenced by variables in subroutine's stack frame.
- Requires us to keep track of which entries in a stack frame are pointers.

**Pros/cons:**

\+ Fairly simple to implement

\+ Fairly low cost

— Does not work when there are circular references. Why?

# MARK AND SWEEP (1)

## Mark and sweep algorithm

- Mark every allocated memory block as useless.
- For every pointer in the static address space and on the stack, mark the block it points to as useful.
- For every block whose status changes from useless to useful, mark the blocks referenced by pointers in this block as useful. Apply this rule recursively.
- Reclaim all blocks marked as useless.

# MARK AND SWEEP (2)

Pros/cons:

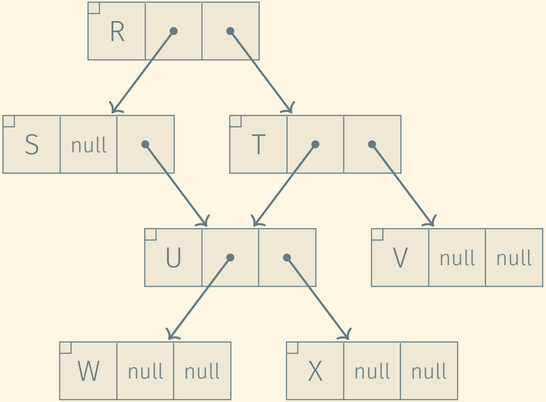
- More complicated to implement.
- Requires inspection of all allocated blocks in a sweep: costly.
- High space usage if the recursion is deep.
- Requires type descriptor at the beginning of each block to know the size of the block and to find the pointers in the block.

# MARK AND SWEEP (2)

Pros/cons:

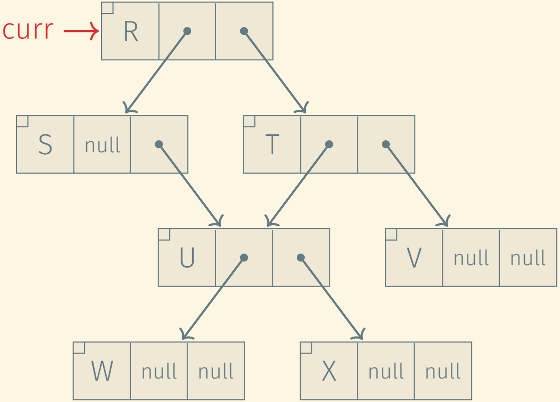
- — More complicated to implement.
- — Requires inspection of all allocated blocks in a sweep: costly.
- — High space usage if the recursion is deep.
- — Requires type descriptor at the beginning of each block to know the size of the block and to find the pointers in the block.
- \+ Works with circular data structures.

# SPACE-EFFICIENT MARK AND SWEEP



# SPACE-EFFICIENT MARK AND SWEEP

back = null



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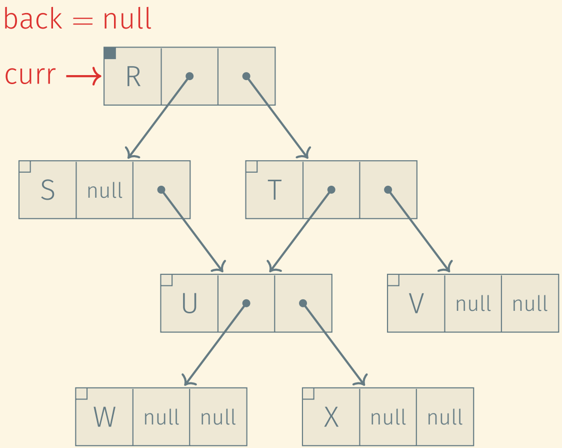

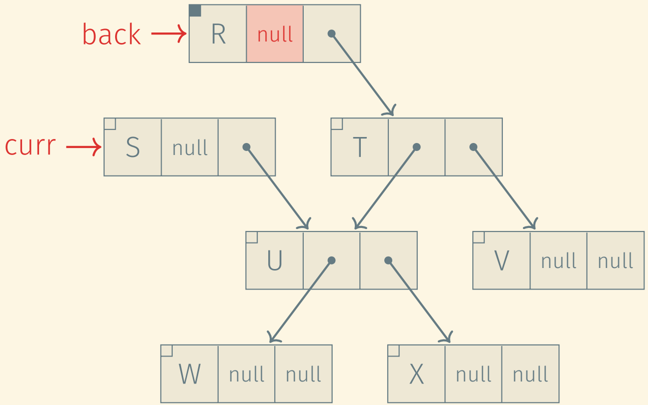
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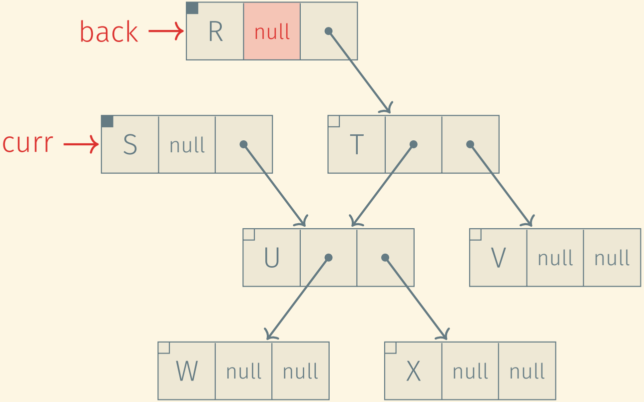
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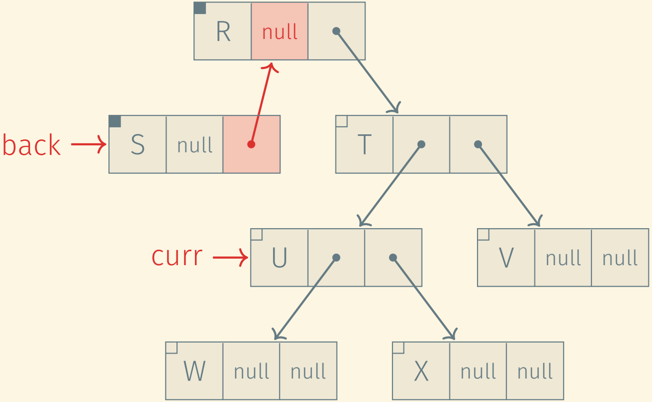

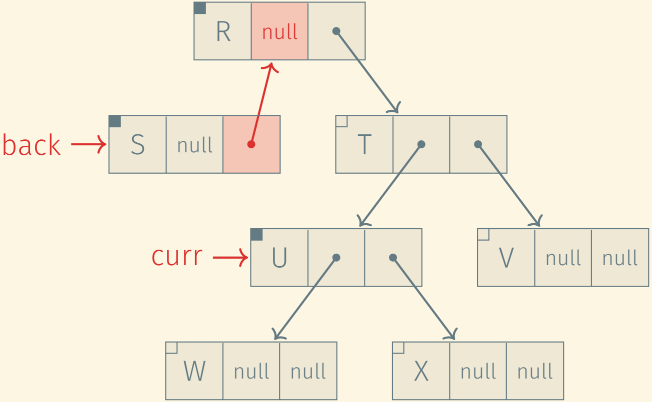
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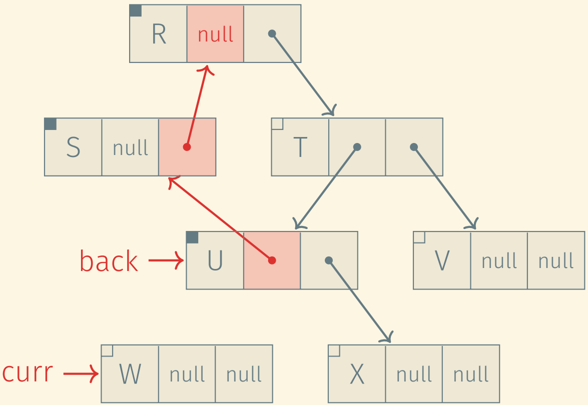
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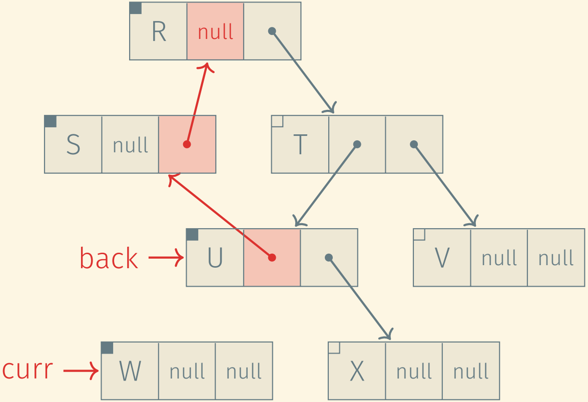
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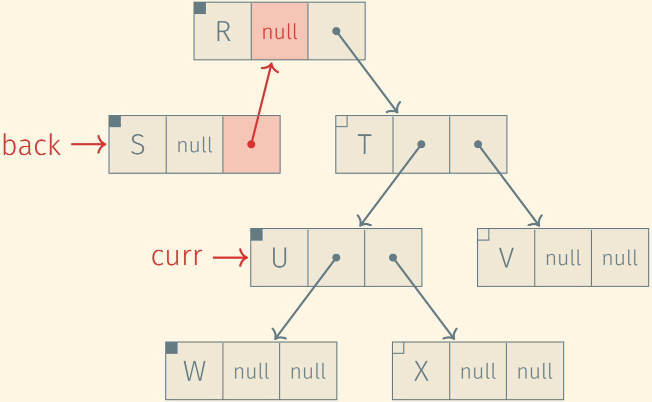

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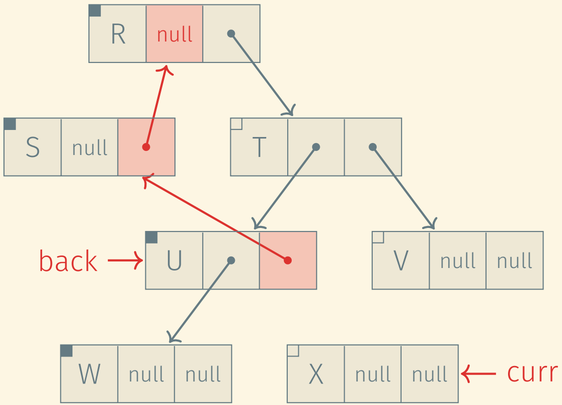

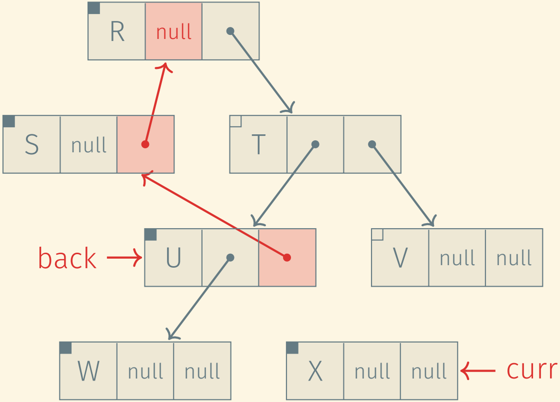
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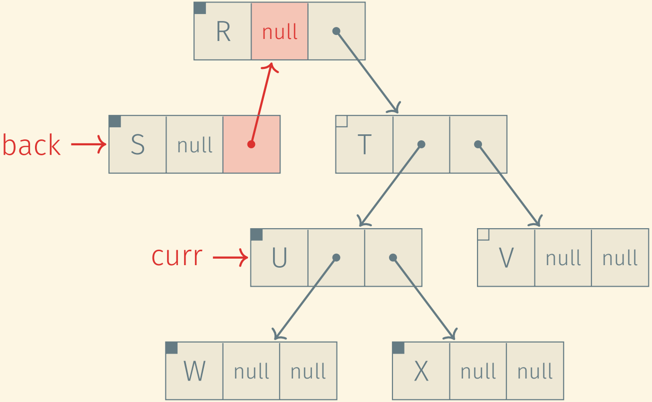

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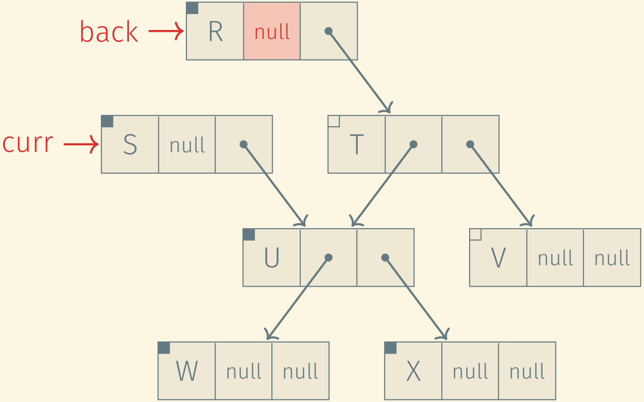

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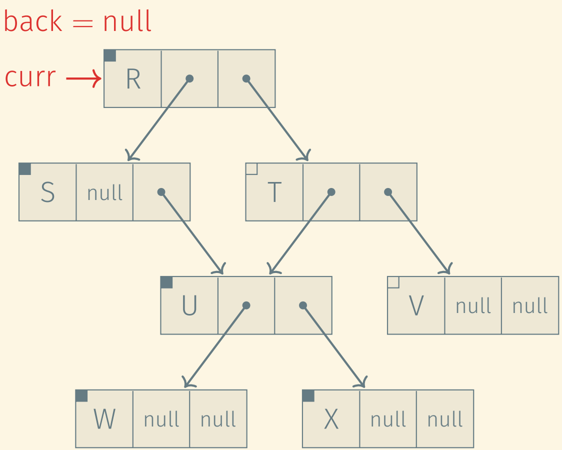

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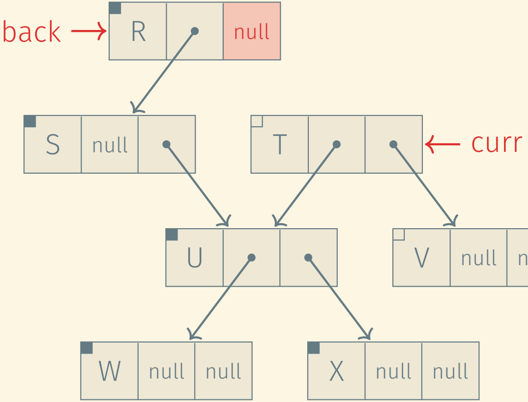

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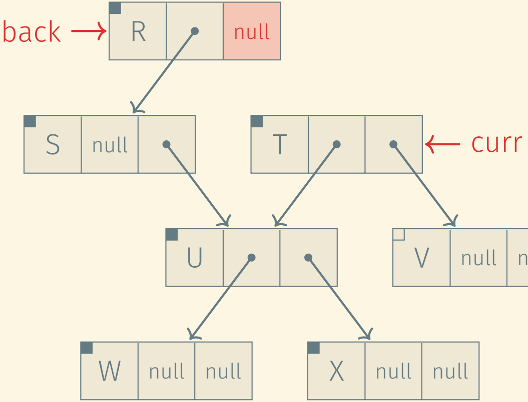

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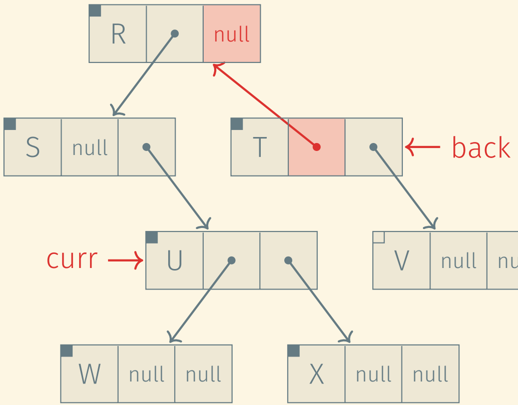

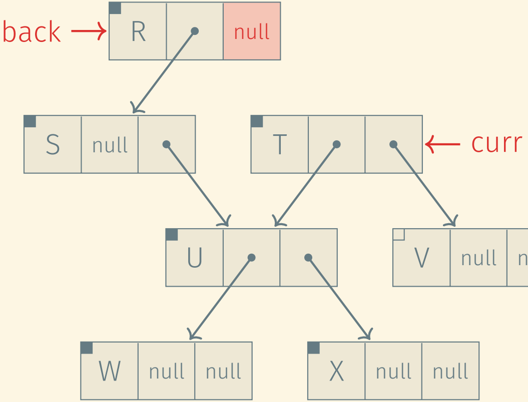
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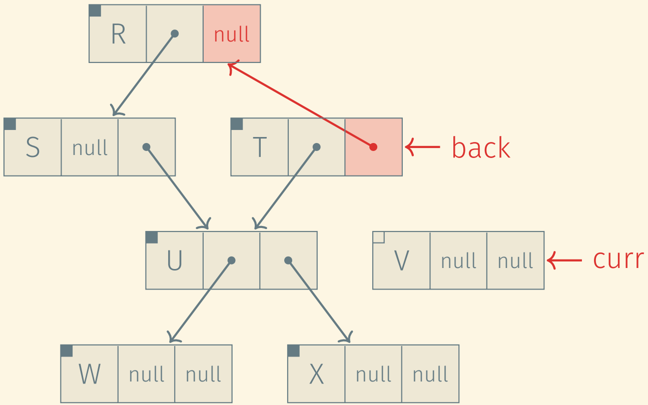

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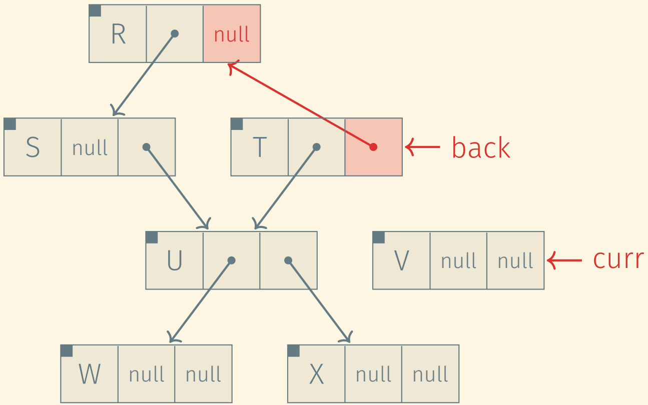

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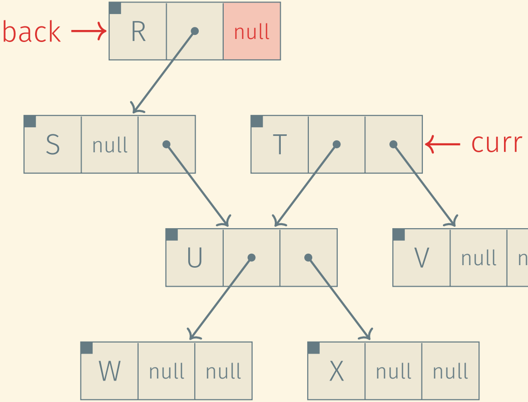
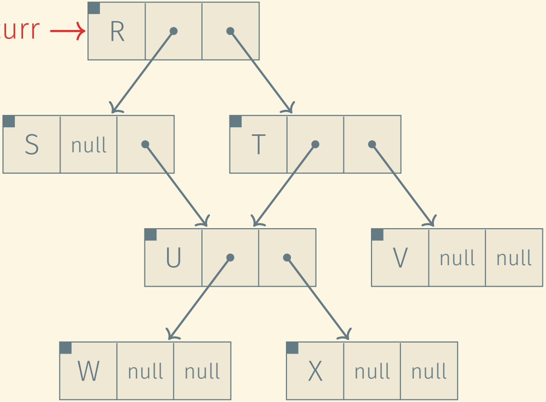
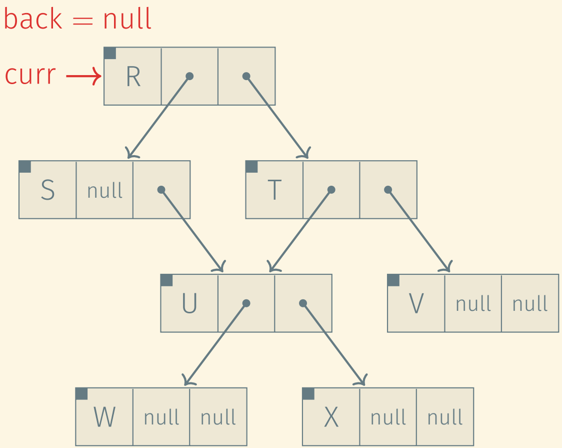


back = null

curr →






**Space:** $1 + \lceil \log_2 f \rceil$ bits per record ($f$ = number of fields in record)

# MARK AND SWEEP VARIANT: STOP AND COPY (1)

## Stop and copy algorithm

- Heap is divided into two halves. Allocation happens in the first half.
- Once the first half is full, start garbage collection and compaction:
    - Find useful objects as in standard mark and sweep but without first marking objects as useless.
    - Copy every useful object to the second half of the heap and replace it with a tag pointing to the new location.
    - Replace every subsequent pointer to this object with a pointer to the new copy.
    - Swap the roles of the two halves.

Pros/cons:

+ Time proportional to the number of useful objects, not total number of objects.
+ Eliminates external fragmentation.
± Only half the heap is available for allocation. Not really an issue if we have virtual memory.

# MARK AND SWEEP VARIANT: GENERATIONAL GARBAGE COLLECTION (1)

## Generational garbage collection

- Heap is divided into several (often two) regions.
- Allocation happens in the first region.
- Garbage collection:
    - Apply mark and sweep to the first region.
    - Promote every object that survives a small number (often one) of rounds of garbage collection in a region to the next region in a manner similar to stop and copy.
    - Inspect (mark and sweep) subsequent regions only if collection in the regions inspected so far did not free up enough space.

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  - Inspect (mark and sweep) subsequent regions only if collection in the regions inspected so far did not free up enough space.

**Idea:** Most objects are short-lived. Collection mostly inspects only the first region and is thus cheaper.

# MARK AND SWEEP VARIANT: GENERATIONAL GARBAGE COLLECTION (1)

Two main issues:

- How to discover useful objects in a region without searching the other regions?
- How to update pointers from older regions to younger regions when promoting objects?

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- How to update pointers from older regions to younger regions when promoting objects?

Techniques:

- Disallow pointers from old regions to young regions by moving objects around appropriately.
- Keep list of old-to-new pointers. (Requires instrumentation $\Rightarrow$ runtime overhead.)

# CONSERVATIVE GARBAGE COLLECTION

Normally, garbage collectors need to know which positions in an object are pointers. This requires a type descriptor to be stored with each object (space overhead).

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Assume every word is a pointer and mark every memory block referenced by such a “pointer” as useful.

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This may fail to reclaim useless objects because some integer or other value happens to equal the address of the object when interpreted as a pointer.

Statistically, this is rare.

## SUMMARY

- A language's type system determines the data abstractions we can build.
- Common types include records, arrays, lists (built from records), pointers, ...
- Pointers to heap-allocated objects require us to manage these objects.
- Garbage collection relieves us of the need to explicitly manage heap-allocated objects but has a runtime cost and is non-trivial.