

## Symbol Tables

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For compile-time efficiency, compilers often use a symbol table:

- associates lexical *names* (symbols) with their *attributes*

What items should be entered?

- variable names
- defined constants
- procedure and function names
- literal constants and strings
- source text labels
- compiler-generated temporaries

Separate table for structure layouts (types - field offsets and lengths)

## Symbol Table Information

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What kind of information might the compiler need?

- textual name
- data type
- dimension information (for aggregates)
- declaring procedure
- lexical level of declaration
- storage class (base address)
- offset in storage
- if record, pointer to structure table
- if parameter, by-reference or by-value?
- can it be aliased? to what other names?
- number and type of arguments to functions

## Symbol table organization

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How should the table be organized?

### *Linear List*

- $O(n)$  probes per lookup
- easy to expand — no fixed size
- one allocation per insertion

### *Ordered Linear List*

- $O(\log_2 n)$  probes per lookup using binary search
- insertion is expensive (to reorganize list)

### *Binary Tree*

- $O(n)$  probes per lookup — unbalanced
- $O(\log_2 n)$  probes per lookup — balanced
- easy to expand — no fixed size
- one allocation per insertion

### *Hash Table*

- $O(1)$  probes per lookup — on average
- expansion costs vary with specific scheme

## Hash Tables

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What about the hash function?

Properties:

- $h(c_1c_2\dots c_k)$  depends solely on  $c_1c_2\dots c_k$
- $h$  computed quickly
- *uniform* — equal probability of all hash values
- *randomizing* — similar symbols have dissimilar hash values

Examples: for table size  $m$ ,  $h(c_1c_2\dots c_k) =$

1.  $(c_1 \times c_k) \bmod m$
2.  $(\sum_{i=1}^k c_i) \bmod m$
3.  $(\prod_{i=1}^k c_i) \bmod m$
4.  $h_k$  where  $h_0 = 0$  and  $h_i = \alpha h_{i-1} + c_i, 1 \leq i \leq k, \alpha$  prime

## Hash Tables: Resolving Collisions

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### *Linear resolution*

- try  $(h(c_1c_2\dots c_k) + i) \bmod m, i = 1, 2, 3, \dots$
- problem: long chains as table fills

### *Add-the-hash rehash*

- try  $i \times h(c_1c_2\dots c_k) \bmod m, i = 2, 3, \dots$
- prevents long chains, but  $m$  must be prime to eventually cover all hash values

### *Quadratic rehash*

- try  $(h(c_1c_2\dots c_k) + i^2) \bmod m, i = 1, 2, 3, \dots$

### *Chaining (bucket hash table)*

- minimizes table space overhead
- graceful performance degradation as table fills

## Bucket Hash Table

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Combine sparse index and a linear list

Lookup and Insertion

1. hash into one of  $m$  buckets
2. walk the bucket's list checking for item
3. if not found, add to front of list

Average case complexity –  $n$  elements,  $m$  buckets

- *lookup* — walk half the list  $O(1 + \frac{n}{2m})$
- *insertion* — walk the entire list  $O(2 + \frac{n}{m})$

Can we improve on the linear search?

## Bucket Hash Table

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### Scheme 1

On each lookup, move item to front of bucket list

- capitalize on locality, if possible
- reduce average case search

### Scheme 2

On each lookup, move item up by one position

- capitalize on locality, if possible
- limit impact of a single lookup
- reduce average case search

## Linear Rehash Table

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Use simple linear table and rehash on collision

Lookup and Insertion

1. Hash into an index
2. If Table[index] is empty
  - (a) lookup fails
  - (b) insertion adds at index
3. If Table[index] is full
  - (a) match implies lookup succeeds
  - (b) no match or insertion implies pick new index and goto step 2 (full table?)

Key issues

- Step 3b — simply add  $k$  to index
- table size should be prime (at least odd)
- $k$  and table size should be relatively prime

## Linear Rehash Table

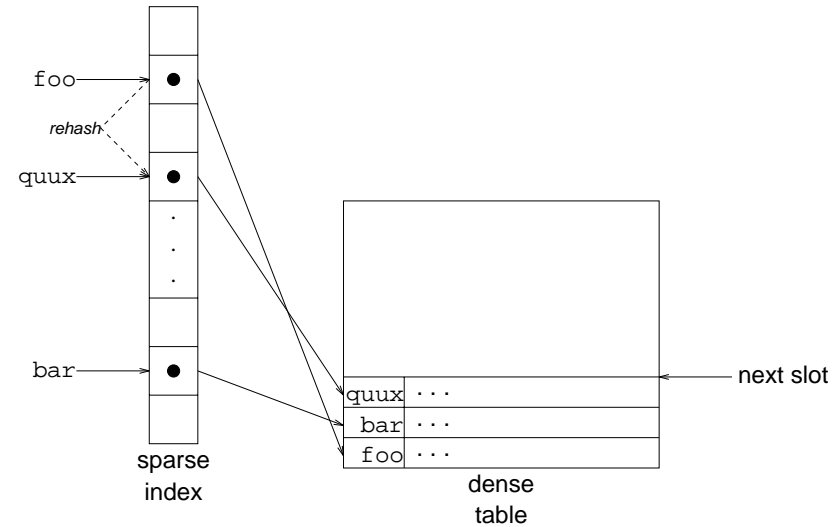
### Scheme 1: Simple Table

- use a simple, sparse table
- moderately large data structure
- fixed size table
- reallocation is terrible

### Scheme 2: Complex Table

- use a sparse map
- use a dense table
- table growth is easy
- map growth and rehash is simple
- file I/O simplified

## Example



## Nested Scopes: Block-Structured Symbol Tables

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What information is needed?

- when we ask about a name, we want the *most recent* declaration
- the declaration may be from the current scope or some enclosing scope
- innermost scope overrides declarations from outer scopes

Key point: new declarations (usually) occur only in current scope

What operations do we need?

- $insert(name, p)$  — create record for  $name$  at level  $p$
- $lookup(name)$  — returns pointer or index
- $delete(p)$  — deletes all names declared at level  $p$

May need to preserve list of locals for the debugger

## Nested Scopes

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Idea 1: Chain together procedure local hash tables

- $insert(name, p)$  adds to the level  $p$  table  
It may need to create the level  $p$  table and add it to the chain
- $lookup(name)$  walks chain of tables, looking in each  
Returns first occurrence of  $name$
- $delete(p)$  throws away table for level  $p$   
It must be the top table on chain

## Nested Scopes

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Idea 2: Build on a bucket hash organization

- $insert(name, p)$  adds  $(name, p)$  to the front of the bucket list  
Chain together records declared at level  $p$
- $lookup(name)$  naturally finds lexically closest definition
- $delete(p)$  walks the level  $p$  chain  
It removes each level  $p$  item and fixes up the pointers

Chain reorganization is more complex, but doable

## Nested Scopes

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Idea 3: Build on a linear rehash scheme

- $insert(name, p)$  hashes by  $name$ .
  1. If  $name$  isn't found, add it.
  2. If  $name$  is there with wrong level,
    - (a) create hidden name record
    - (b) hang it off table slot
    - (c) supersede information in active slot
  3. Add  $name$  to level  $p$  chain
- $lookup(name)$  works without change
- $delete(p)$  walks the level  $p$  chain for each  $name$  on the chain
  1. update the active record from front of chain
  2. deletes the first hidden name record from chain

## Nested Scopes: Complications

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Fields and records — either give each record type its own symbol table *or* assign record numbers to qualify field names in symbol table

**with R do** <stmt>:

- all IDs in <stmt> are treated first as R.id
- separate record tables — chain R's scope ahead of outer scopes
- record numbers — either open new scope, copy entries with R's record number *or* chain record numbers: search using these first

Implicit declarations:

- labels — declare and define name
- Ada/Modula-3/Tiger FOR loop: loop index has type of range specifier

Overloading:

- link alternatives (check no clashes), choose based on context

Forward references:

- bind symbol only after all possible definitions  
⇒ multiple passes

Other complications:

- packages, modules, interfaces — IMPORT, EXPORT

## Attribute Information

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Attributes are internal representation of declarations

Symbol table associates names with attributes

Names may have different attributes depending on their meaning:

- variables: type, procedure level, frame offset
- types: type descriptor, data size/alignment
- constants: type, value
- procedures: formals (names/types), result type, block information (local decls.), frame size

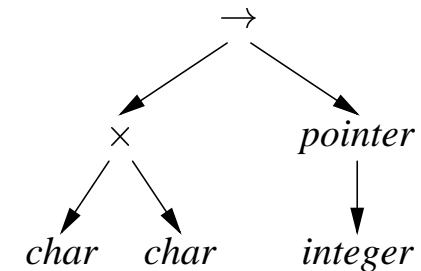
## Type Expressions

Type expressions are a textual representation for types:

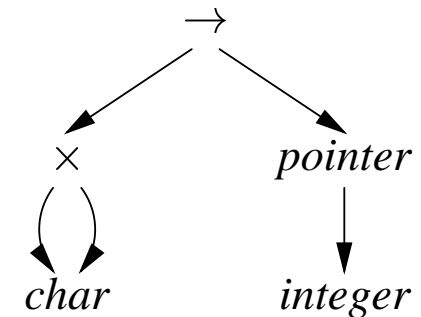
1. basic types: *boolean*, *char*, *integer*, *real*, etc.
2. type names
3. constructed types (constructors applied to type expressions):
  - (a) arrays:  $array(I, T)$  denotes array of elements of type  $T$ , index type  $I$   
e.g.,  $array(1..10, integer)$
  - (b) products:  $T_1 \times T_2$  denotes the Cartesian product of type expressions  $T_1$  and  $T_2$
  - (c) records: fields have names  
e.g.,  $record((a \times integer), (b \times real))$
  - (d) pointers:  $pointer(T)$  denotes the type “pointer to an object of type  $T$ ”
  - (e) functions:  $D \rightarrow R$  denotes type of a function mapping domain type  $D$  to range type  $R$   
e.g.,  $integer \times integer \rightarrow integer$

## Type Descriptors

Type descriptors are compile-time structures representing type expressions  
e.g.,  $char \times char \rightarrow pointer(integer)$



or



## Type Compatibility

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Type checking needs to determine type equivalence

Two approaches:

*Name equivalence*: each type name is a distinct type

*Structural equivalence*: two types are equivalent iff. they have the same structure (after substituting type expressions for type names)

- $s \equiv t$  iff.  $s$  and  $t$  are the same basic types
- $array(s_1, s_2) \equiv array(t_1, t_2)$  iff.  $s_1 \equiv t_1$  and  $s_2 \equiv t_2$
- $s_1 \times s_2 \equiv t_1 \times t_2$  iff.  $s_1 \equiv t_1$  and  $s_2 \equiv t_2$
- $pointer(s) \equiv pointer(t)$  iff.  $s \equiv t$
- $s_1 \rightarrow s_2 \equiv t_1 \rightarrow t_2$  iff.  $s_1 \equiv t_1$  and  $s_2 \equiv t_2$

## Type Compatibility: Example

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Consider:

```

type link = ↑cell;
var  next : link;
      last  : link;
      p     : ↑cell;
      q, r  : ↑cell;

```

Under name equivalence:

- next and last have the same type
- p, q and r have the same type
- p and next have different type

Under structural equivalence all variables have the same type

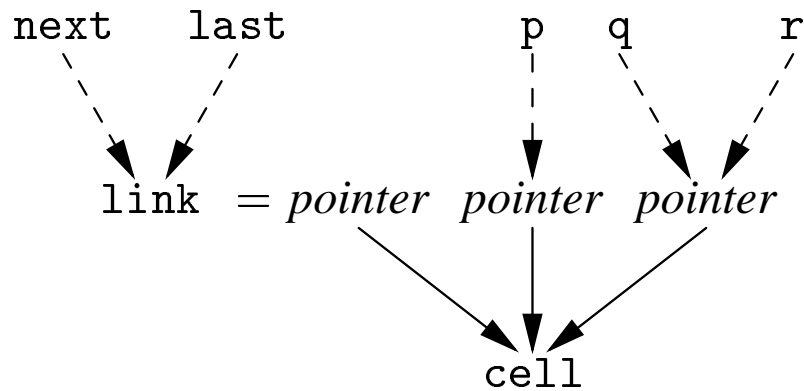
Ada/Pascal/Modula-2/Tiger are somewhat confusing they treat distinct type definitions as distinct types, so:

p has different type from q and r

## Type Compatibility: Pascal-Style Name Equivalence

Build compile-time structure called a *type graph*:

- each constructor or basic type creates a node
- each name creates a leaf (associated with the type's descriptor)



Type expressions are equivalent if they are represented by the same node in the graph

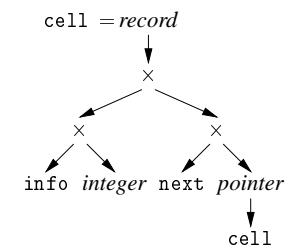
## Type Compatibility: Recursive Types

Consider:

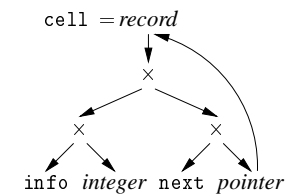
```

type link = ↑cell;
        cell = record;
                info : integer;
                next  : link;
                end;
  
```

We may want to eliminate the names from the type graph. Eliminating name link from type graph for record:



Allowing cycles in the type graph eliminates cell:



## Overloading

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Most languages have type overloading:

- If nothing else, for integers/floats
- Equality/assignment overloaded for almost anything
- In languages with dynamic types (Lisp, Smalltalk), decision on what to do depends on type check at run-time
- Very inefficient for integers/floats
- Can be resolved at compile-time by *type inference*
- Type inference is usually done bottom-up
  - Say we have  $f$  can be either  $int \rightarrow int$  or  $float \rightarrow float$
  - Then  $f(42)$  has only one valid typing:  $int$

## Polymorphic Functions

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Polymorphism = many shapes

- Ad-hoc polymorphism: on a case-by-case basis; overloading
- Parametric polymorphism: can take a type as an argument
  - Templates
  - “True” parametric polymorphism:
    - \* function  $length(L) = \text{if } null(L) \text{ then } 0 \text{ else } 1 + length \text{ tail}(L)$
    - \*  $length: List(\alpha) \rightarrow int$
    - \* function  $first(L) = head(L)$
    - \*  $first: List(\alpha) \rightarrow \alpha$
    - \* function  $reverse(l) = \dots$
    - \*  $reverse: List(\alpha) \rightarrow List(\alpha)$
  - Often combined with type inference