Semantic Processing

The compilation process is driven by the syntactic structure of the program as discovered by the parser

Semantic routines:

- interpret meaning of the program based on its syntactic structure
- two purposes:
  - finish analysis by deriving context-sensitive information
  - begin synthesis by generating the IR or target code
- associated with individual productions of a context free grammar or subtrees of a syntax tree

Context-sensitive analysis

What context-sensitive questions might the compiler ask?

1. Is `x` scalar, an array, or a function?
2. Is `x` declared before it is used?
3. Are any names declared but not used?
4. Which declaration of `x` does this reference?
5. Is an expression *type-consistent*?
6. Does the dimension of a reference match the declaration?
7. Where can `x` be stored? (heap, stack, ...)
8. Does `*p` reference the result of a malloc()?
9. Is `x` defined before it is used?
10. Is an array reference *in bounds*?
11. Does function `foo` produce a constant value?
12. Can `p` be implemented as a *memo-function*?

These cannot be answered with a context-free grammar

Context-sensitive analysis

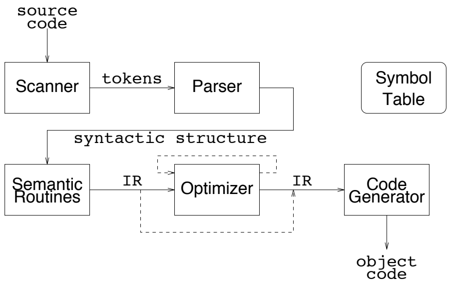
Why is context-sensitive analysis hard?

- answers depend on values, not syntax
- questions and answers involve non-local information
- answers may involve computation

Several alternatives:

abstract syntax tree (*attribute grammars*)	specify non-local computations automatic evaluators
symbol tables	central store for facts express checking code
language design	simplify language avoid problems

Alternatives for semantic processing



- one-pass analysis and synthesis
- one-pass compiler plus peephole
- one-pass analysis & IR synthesis + code generation pass
- multipass analysis (MiniJava)
- multipass synthesis (MiniJava)
- language-independent and retargetable compilers (MiniJava)

One-pass compilers

- interleave scanning, parsing, checking, and translation
- no explicit IR
- generates target machine code directly
  emit short sequences of instructions at a time on each parser action (symbol match for predictive parsing/LR reduction)
  ⇒ little or no optimization possible (minimal context)

Can add a *peephole optimization pass*

- extra pass over generated code through window (*peephole*) of a few instructions
- smoothes “rough edges” between segments of code emitted by one call to the code generator

One-pass analysis/synthesis + code generation

Generate explicit IR as interface to code generator

- linear – e.g., tuples
- code generator alternatives:
  - one tuple at a time
  - many tuples at a time for more context and better code

Advantages

- back-end independent from front-end
  ⇒ easier retargetting
  IR must be expressive enough for different machines
- add optimization pass later (multipass synthesis)

Multipass analysis

Historical motivation: constrained address spaces

Several passes, read/write intermediate code files

1. scan source file, generate tokens (place identifiers and constants directly into symbol table)
2. parse token file
   generate *semantic actions* or linearized parse tree
3. parser output drives:
   - declaration processing to symbol table file
   - semantic checking with synthesis of code/linear IR

Multipass analysis

Other reasons for multipass analysis (omitting file I/O)

- language may require it – e.g., declarations after use:
  1. scan, parse and build symbol table
  2. semantic checks and code/IR synthesis
- take advantage of tree-structured IR for less restrictive analysis: scanning, parsing, tree generation combined, one or more subsequent passes over the tree perform semantic analysis and synthesis

Multipass synthesis

Passes operate on linear or tree-structured IR

Options

- code generation and peephole optimization
- multipass transformation of IR: machine-independent and machine-dependent optimizations
- high-level machine-independent IR to lower-level IR prior to code generation
- language-independent front ends (first translate to high-level IR)
- retargettable back ends (first transform into low-level IR)

Multipass synthesis: e.g., GNU C compiler (`gcc`)

- language-dependent parser builds language-independent trees
- trees drive generation of machine-independent low-level **R**egister **T**ransfer **L**anguage for machine-independent optimization
- thence to target machine code and peephole optimization

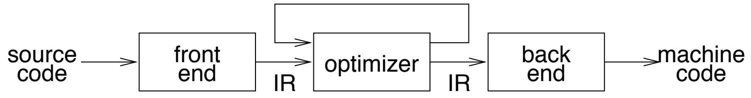
Intermediate representations

Why use an intermediate representation?

1. break the compiler into manageable pieces
   good software engineering technique
2. allow a complete pass before code is emitted
   lets compiler consider more than one option
3. simplifies retargeting to new host
   isolates back end from front end
4. simplifies handling of “poly-language/architecture” problem
   m lang’s, n targets $\Rightarrow$ $m+n$ components (*myth*)
5. enables machine-independent optimization
   general techniques, multiple passes

An intermediate representation is a compile-time data structure

Intermediate representations



source code

front end

IR

optimizer

IR

back end

machine code

Generally speaking:

- front end produces IR
- optimizer transforms that representation into an equivalent program that may run more efficiently
- back end transforms IR into native code for the target machine

Intermediate representations

Representations talked about in the literature include:

- abstract syntax trees (AST)
- linear (operator) form of tree
- directed acyclic graphs (DAG)
- control flow graphs (CFG)
- program dependence graphs (PDG)
- static single assignment form (SSA)
- 3-address code
- hybrid combinations

Intermediate representations

Important IR Properties

- ease of generation
- ease of manipulation
- cost of manipulation
- level of abstraction
- freedom of expression
- size of typical procedure
- original or derivative

Subtle design decisions in the IR have far reaching effects on the speed and effectiveness of the compiler.

Level of exposed detail is a crucial consideration.

Intermediate representations

Broadly speaking, IRs fall into three categories:

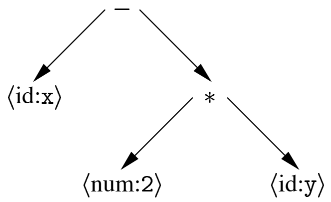
Structural
  - structural IRs are graphically oriented
  - examples include trees, DAGs
  - heavily used in source to source translators
  - nodes, edges tend to be large

Linear
  - pseudo-code for some abstract machine
  - large variation in level of abstraction
  - simple, compact data structures
  - easier to rearrange

Hybrids
  - combination of graphs and linear code
  - attempt to take best of each
  - e.g., control-flow graphs

Abstract syntax tree

An abstract syntax tree (AST) is the procedure's parse tree with the nodes for most non-terminal symbols removed.



This represents "$\texttt{x} - 2 * \texttt{y}$".

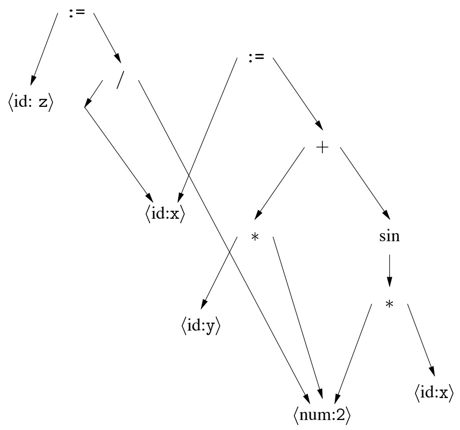
For ease of manipulation, can use a linearized (operator) form of the tree.

e.g., in postfix form: $\texttt{x}\ 2\ \texttt{y} * -$

Directed acyclic graph

A directed acyclic graph (DAG) is an AST with a unique node for each value.

```
x := 2 * y + sin(2*x)
z := x / 2
```

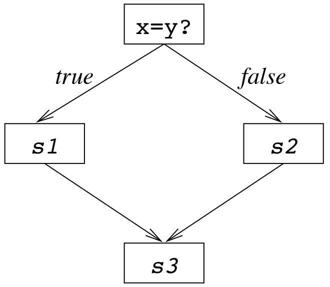


Control flow graph

The control flow graph (CFG) models the transfers of control in the program

- nodes are *basic blocks*
  straight-line blocks of code
- edges in the graph represent control flow
  loops, if-then-else, case, goto

```
if x = y then
  S1
else
  S2
end
S3
```



3-address code

3-address code can mean a variety of representations.

In general, it allow statements of the form:

```
x = y op z
```

with a single operator and, at most, three names.

Simpler form of expression:

```
x - 2 * y
```

becomes

```
t1 = 2 * y
t2 = x - t1
```

Advantages

- compact form (direct naming)
- names for intermediate values

Can include forms of prefix or postfix code

3-address code

Typical statement types include:

1. assignments
   `x = y op z`
2. assignments
   `x = op y`
3. assignments
   `x = y[i]`
4. assignments
   `x = y`
5. branches
   `goto L`
6. conditional branches
   `if x relop y goto L`
7. procedure calls
   ```
   param x
   param y
   call p
   ```
8. address and pointer assignments
   ```
   x = &y
   *y = z
   ```

3-address code

Quadruples

`x - 2 * y`

(1)	load	t1	y	
(2)	loadi	t2	2	
(3)	mult	t3	t2	t1
(4)	load	t4	x	
(5)	sub	t5	t4	t3

- simple record structure with four fields
- easy to reorder
- explicit names

3-address code

Triples

`x - 2 * y`

(1)	load	y	
(2)	loadi	2	
(3)	mult	(1)	(2)
(4)	load	x	
(5)	sub	(4)	(3)

- use table index as implicit name
- require only three fields in record
- harder to reorder

3-address code

Indirect Triples

`x - 2 * y`

	stmt		op	arg1	arg2
(1)	(100)	(100)	load	y	
(2)	(101)	(101)	loadi	2	
(3)	(102)	(102)	mult	(100)	(101)
(4)	(103)	(103)	load	x	
(5)	(104)	(104)	sub	(103)	(102)

- list of 1st triple in statement
- simplifies moving statements
- more space than triples
- implicit name space management

Other hybrids

An attempt to get the best of both worlds.

- graphs where they work
- linear codes where it pays off

Unfortunately, there appears to be little agreement about where to use each kind of IR to best advantage.

For example:

- PCC and FORTRAN 77 directly emit assembly code for control flow, but build and pass around expression trees for expressions.
- Many people have tried using a control flow graph with low-level, three address code for each basic block.

Intermediate representations

But, this isn't the whole story

Symbol table:

- identifiers, procedures
- size, type, location
- lexical nesting depth

Constant table:

- representation, type
- storage class, offset(s)

Storage map:

- storage layout
- overlap information
- (virtual) register assignments

Advice

- Many kinds of IR are used in practice.
- There is no widespread agreement on this subject.
- A compiler may need several different IRs
- Choose IR with right level of detail
- Keep manipulation costs in mind

For MiniJava:

1. abstract syntax trees separate syntax analysis from semantic analysis
2. intermediate code trees separate semantic analysis from code generation

Semantic actions

Parser must do more than accept/reject input; must also initiate translation.

Semantic actions are routines executed by parser for each syntactic symbol recognized.

Each symbol has associated *semantic value* (e.g., parse tree node).

Recursive descent parser:

- one routine for each non-terminal
- routine returns semantic value for the non-terminal
- store semantic values for RHS symbols in local variables

What about a table-driven LL(1) parser?

- maintain explicit *semantic stack* distinct from parse stack
- actions push results and pop arguments

LL parsers and actions

How does an LL parser handle actions?

Expand productions *before* scanning RHS symbols, so:

- push actions onto parse stack like other grammar symbols
- pop and perform action when it comes to top of parse stack

LL parsers and actions

```
push EOF
push Start Symbol
token ← next_token()
repeat
    pop X
    if X is a terminal or EOF then
        if X = token then
            token ← next_token()
        else error()
    else if X is an action
        perform X
    else /* X is a non-terminal */
        if $M$[X,token] = $X \rightarrow Y_1 Y_2 \cdots Y_k$ then
            push $Y_k, Y_{k-1}, \cdots, Y_1$
        else error()
until X = EOF
```

LR parsers and action symbols

What about LR parsers?

Scan entire RHS before applying production, so:

- cannot perform actions until entire RHS scanned
- can only place actions at very end of RHS of production
- introduce new marker non-terminals and corresponding productions to get around this restriction[†]

$$A \rightarrow w\ \textit{action}\ \beta$$

becomes

$$A \rightarrow M\beta$$

$$M \rightarrow w\ \textit{action}$$

[†] yacc, bison, CUP do this automatically

Action-controlled semantic stacks

Approach:

- stack is managed explicitly by action routines
- actions take arguments from top of stack
- actions place results back on stack

Advantages:

- actions can directly access entries in stack without popping (efficient)

Disadvantages:

- implementation is exposed
- action routines must include explicit code to manage stack

Alternative: *abstract semantic stacks*

- hide stack implementation behind `push`, `pop` interface
- accessing stack entries now requires `pop` (and copy to local var.)
- still need to manage stack within actions ⇒ errors

LR parser-controlled semantic stacks

Idea: let parser manage the semantic stack

LR parser-controlled semantic stacks:

- parse stack contains already parsed symbols
- maintain semantic values in parallel with their symbols
- add space in parse stack or parallel stack for semantic values
- every matched grammar symbol has semantic value
- pop semantic values along with symbols

⇒ LR parsers have a very nice fit with semantic processing

LL parser-controlled semantic stacks

Problems:

- parse stack contains predicted symbols, not yet matched
- often need semantic value after its corresponding symbol is popped

Solution:

- use separate semantic stack
- push entries on semantic stack along with their symbols
- on completion of production, pop its RHS's semantic values

Attribute grammars

Idea: attribute the syntax tree

- can add attributes (*fields*) to each node
- specify equations to define values (*unique*)
- can use attributes from parent and children

Example: to ensure that constants are immutable:

- add *type* and *class* attributes to expression nodes
- rules for production on `:=` that
  1. check that LHS.*class* is *variable*
  2. check that LHS.*type* and RHS.*type* are consistent or conform

Attribute grammars

To formalize such systems Knuth introduced *attribute grammars*:

- grammar-based specification of tree attributes
- value assignments associated with productions
- each attribute uniquely, locally defined
- label identical terms uniquely

Can specify context-sensitive actions with attribute grammars

Example

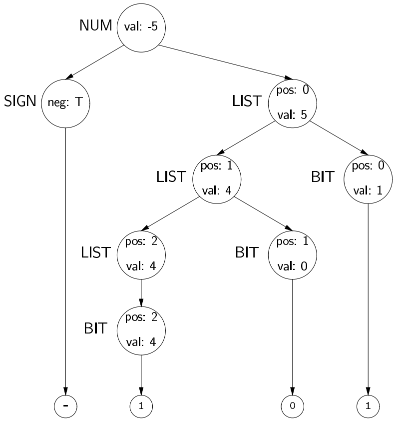
PRODUCTION	SEMANTIC RULES
$D \rightarrow T\ L$	$L.\text{in} := T.\text{type}$
$T \rightarrow$ **int**	$T.\text{type} := \text{integer}$
$T \rightarrow$ **real**	$T.\text{type} := \text{real}$
$L \rightarrow L_1$, **id**	$L_1.\text{in} := L.\text{in}$ $\text{addtype}(\textbf{id}.\text{entry}, L.\text{in})$
$L \rightarrow$ **id**	$\text{addtype}(\textbf{id}.\text{entry}, L.\text{in})$

Example: Evaluate signed binary numbers

PRODUCTION	SEMANTIC RULES
NUM → SIGN LIST	LIST.pos := 0
	if SIGN.neg
	NUM.val := -LIST.val
	else
	NUM.val := LIST.val
SIGN → +	SIGN.neg := false
SIGN → -	SIGN.neg := true
LIST → BIT	BIT.pos := LIST.pos
	LIST.val := BIT.val
LIST → LIST_1 BIT	LIST_1.pos := LIST.pos + 1
	BIT.pos := LIST.pos
	LIST.val := LIST_1.val + BIT.val
BIT → 0	BIT.val := 0
BIT → 1	BIT.val := $2^{\text{BIT}.pos}$

Example (continued)

The attributed parse tree for `-101`:



- *val* and *neg* are *synthetic* attributes
- *pos* is an *inherited* attribute

Dependences between attributes

- values are computed from constants & other attributes
- *synthetic attribute* – value computed from children
- *inherited attribute* – value computed from siblings & parent
- *key notion*: induced dependency graph

The attribute dependency graph

- nodes represent attributes
- edges represent flow of values
- graph is specific to parse tree
- size is related to parse tree's size
- can be built alongside parse tree

The dependency graph must be acyclic

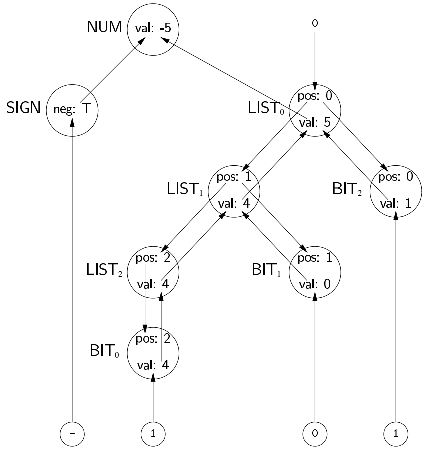
Evaluation order:

- topological sort the dependency graph to order attributes
- using this order, evaluate the rules

The order depends on both the grammar and the input string

Example (continued)

The attribute dependency graph:



Example: A topological order

1. SIGN.neg
2. LIST_0.pos
3. LIST_1.pos
4. LIST_2.pos
5. BIT_0.pos
6. BIT_1.pos
7. BIT_2.pos
8. BIT_0.val
9. LIST_2.val
10. BIT_1.val
11. LIST_1.val
12. BIT_2.val
13. LIST_0.val
14. NUM.val

Evaluating in this order yields NUM.val: -5

Evaluation strategies

Parse-tree methods (*dynamic*)

1. build the parse tree
2. build the dependency graph
3. topological sort the graph
4. evaluate it (*cyclic graph fails*)

Rule-based methods (*treewalk*)

1. analyse semantic rules at compiler-construction time
2. determine a static ordering for each production's attributes
3. evaluate its attributes in that order at compile time

Oblivious methods (*passes*)

1. ignore the parse tree and grammar
2. choose a convenient order (e.g., left-right traversal) and use it
3. repeat traversal until no more attribute values can be generated

Top-down (LL) on-the-fly one-pass evaluation

L-attributed grammar: given production $A \rightarrow X_1 X_2 \cdots X_n$

- inherited attributes of X_j depend only on:
  1. inherited attributes of A
  2. arbitrary attributes of $X_1, X_2, \cdots X_{j-1}$
- synthetic attributes of A depend only on its inherited attributes and arbitrary RHS attributes
- synthetic attributes of an action depends only on its inherited attributes

i.e., evaluation order:
Inh(A), Inh(X_1), Syn(X_1), $\ldots$, Inh(X_n), Syn(X_n), Syn(A)

This is precisely the order of evaluation for an LL parser

Bottom-up (LR) on-the-fly one-pass evaluation

S-attributed grammar:

- L-attributed
- only synthetic attributes for non-terminals
- actions at far right of a RHS

Can evaluate S-attributed in one bottom-up (LR) pass

Inherited attributes: derive values from constants, parents, siblings

- used to express context (*context-sensitive checking*)
- inherited attributes are more "natural"

We want to use both kinds of attribute

- can *always* rewrite L-attributed LL grammars (using markers and copying) to avoid inherited attribute problems with LR

Bottom-up evaluation of inherited attributes

PRODUCTION	SEMANTIC RULES
$D \rightarrow T\ L$	$L.\text{in} := T.\text{type}$
$T \rightarrow$ **int**	$T.\text{type} := \text{integer}$
$T \rightarrow$ **real**	$T.\text{type} := \text{real}$
$L \rightarrow L_1$, **id**	$L_1.\text{in} := L.\text{in}$ addtype(**id**.entry, L.in)
$L \rightarrow$ **id**	addtype(**id**.entry, L.in)

For copy rules generating inherited attributes value may be found at a fixed offset below top of stack

---

Simulating bottom-up evaluation

Consider:

PRODUCTION	SEMANTIC RULES
$S \rightarrow aAC$	$C.i := A.s$
$S \rightarrow bABC$	$C.i := A.s$
$C \rightarrow c$	$C.s := g(C.i)$

C inherits synthetic attribute $A.s$ by copy rule

There may or may not be a B between A and C in parse stack

Rewrite as:

PRODUCTION	SEMANTIC RULES
$S \rightarrow aAC$	$C.i := A.s$
$S \rightarrow bABMC$	$M.i := A.s; C.i := M.s$
$C \rightarrow c$	$C.s := g(C.i)$
$M \rightarrow \lambda$	$M.s := M.i$

Simulating bottom-up evaluation

Consider:

PRODUCTION	SEMANTIC RULES
$S \rightarrow aAC$	$C.i := f(A.s)$

C inherits $f(A.s)$, but not by copying

Value of $f(A.s)$ is not in the stack

Rewrite as:

PRODUCTION	SEMANTIC RULES
$S \rightarrow aAMC$	$M.i := A.s; C.i := M.s$
$M \rightarrow \lambda$	$M.s := f(M.i)$

Bottom-up (LR) on-the-fly one-pass evaluation

In general, an attribute grammar can be evaluated with one-pass LR if it is LC-attributed:

- L-attributed
- non-terminals in *left corners* have only synthetic attributes
- no actions in *left corners*

Left corners are that part of RHS sufficient to recognize the production, e.g., $A \rightarrow \alpha\beta$

LL(1) ⇒ left corner α is empty
LR(1) ⇒ left corner may be entire RHS
(right corner β may be empty)

Attribute Grammars

Advantages

- clean formalism
- automatic generation of evaluator
- high-level specification

Disadvantages

- evaluation strategy determines efficiency
- increased space requirements
- parse tree evaluators need dependency graph
- results distributed over tree
- circularity testing

Intel's 80286 Pascal compiler used an attribute grammar evaluator to perform context-sensitive analysis.

Historically, attribute grammar evaluators have been deemed too large and expensive for commercial-quality compilers.

Other uses

- the Cornell Program Synthesizer
- generate Ph.D. theses and papers
- odd forms of compiling — VHDL compiler
- structure editors for code, theorems, . . .

Attribute grammars are a powerful formalism

- relatively abstract
- automatic evaluation

Symbol tables

For *compile-time* efficiency, compilers 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 (*we'll get there*)

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

A symbol table is a compile-time structure

Symbol table information

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

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

Nested scopes: block-structured symbol tables

What information is needed?

- when asking about a name, want *most recent* declaration
- declaration may be from current scope or outer scope
- innermost scope overrides outer scope declarations

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

What operations do we need?

- `void put (Symbol key, Object value)` – bind key to value
- `Object get(Symbol key)` – return value bound to key
- `void beginScope()` – remember current state of table
- `void endScope()` – close current scope and restore table to state at most recent open beginScope

May need to preserve list of locals for the debugger

Attribute information

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

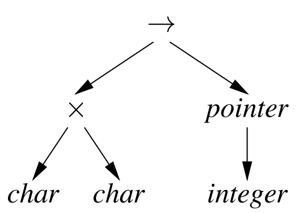
Type expressions are a textual representation for types:

1. basic types: $boolean$, $char$, $integer$, $real$, etc.
2. type names
3. constructed types (constructors applied to type expressions):
   (a) $array(I,T)$ denotes an array of T indexed over I
   e.g., $array(1\dots10, integer)$
   (b) products: $T_1 \times T_2$ denotes Cartesian product of type expressions T_1 and T_2
   (c) records: fields have names
   e.g., $record((\mathtt{a} \times integer), (\mathtt{b} \times real))$
   (d) pointers: $pointer(T)$ denotes the type "pointer to an object of type T"
   (e) functions: $D \rightarrow R$ denotes the type of a function mapping domain type D to range type R
   e.g., $integer \times integer \rightarrow integer$

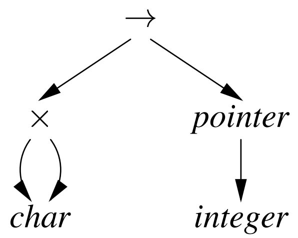
Type descriptors

Type descriptors are compile-time structures representing type expressions

e.g., $char \times char \rightarrow pointer(integer)$



or



Type compatibility

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

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

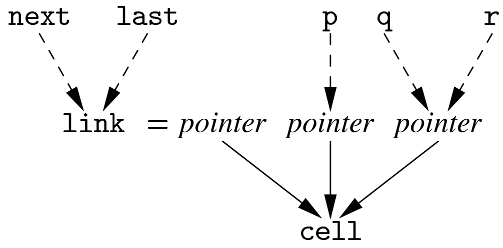
Under structural equivalence all variables have the same type

Ada/Pascal/Modula-2 are somewhat confusing: they treat distinct type definitions as distinct types, so `p` has different type from `q` and `r`

Type compatibility: Pascal 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

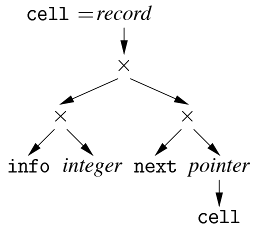
Type compatibility: recursive types

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:



Type compatibility: recursive types

Allowing cycles in the type graph eliminates `cell`: