3. Code Generation

Input: Program in intermediate language

Tasks:

Storage mapping	properties of program objects (size, address) in the definition module
Code selection	generate instruction sequence, optimizing selection
Register allocation	use of registers for intermediate results and for variables

Output: abstract machine program, stored in a data structure

Design of code generation:

- analyze **properties of the target processor**
- plan **storage mapping**
- design at least one **instruction sequence** for each operation of the intermediate language

Implementation of code generation:

- Storage mapping:
  a traversal through the program and the definition module computes
  sizes and addresses of storage objects
- Code selection: use a generator for pattern matching in trees
- Register allocation:
  methods for expression trees, basic blocks, and for CFGs

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3.1 Storage Mapping

Objective:
for each storable program object compute storage class, relative address, size

Implementation:
use properties in the definition module, traverse defined program objects

Design the use of storage areas:

code storage	progam code
global data	to be linked for all compilation units
run-time stack	activation records for function calls
heap	storage for dynamically allocated objects, garbage collection
registers for	addressing of storage areas (e. g. stack pointer) function results, arguments local variables, intermediate results (**register allocation**)

Design the mapping of data types (next slides)
Design activation records and translation of function calls (next section)

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Storage Mapping for Data Types

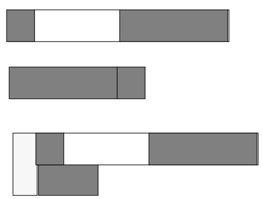
Basic types

arithmetic, boolean, character types

match language requirements and machine properties:
data format, available instructions,
size and alignment in memory

Structured types

for each type	representation in memory and code sequences for operations, e. g. assignment, selection, ...
record	relative address and alignment of components; reorder components for optimization
union	storage overlay, tag field for discriminated union
set	bit vectors, set operations



for **arrays** and **functions** see next slides

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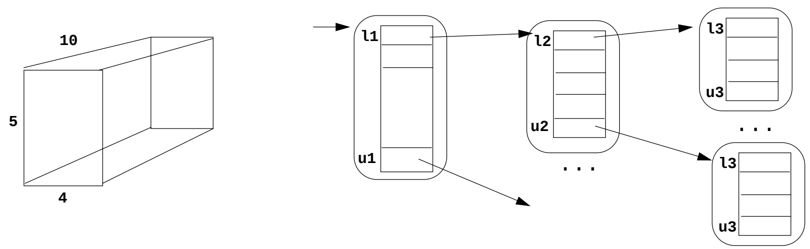
Array Implementation: Pointer Trees

An n-dimensional array

```
a: array[l1..u1, l2..u2, ..., ln..un] of real;
```

is implemented by a **tree of linear arrays**;
n-1 levels of pointer arrays and data arrays on the n-th level



Each single array can be allocated separately, dynamically; scattered in memory

In **Java arrays** are implemented this way.

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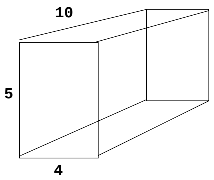
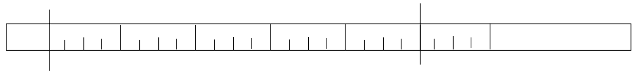
Array Implementation: Contiguous Storage

An n-dimensional array

```
a: array[l1..u1, l2..u2, ..., ln..un] of real;
```

is mapped to **one contiguous storage area** **linearized in row-major order**:





`start`
`store[start] ... store[start + elno*elsz - 1]`

linear storage map of array a onto byte-array `store` from index `start`:

number of elements	`elno = st1 * st2 * ... * stn`
i-th index stride	`sti = ui - li + 1`
element size in bytes	`elsz`

Index map of `a[i1, i2, ..., in]`:

```
store[start+ (..((i1-l1)*st2 + (i2-l2))*st3 +..)*stn + (in-ln))*elsz]

store[const + (..(i1*st2     + i2)*st3     +..)*stn +  in)*elsz]
```

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Functions as Data Objects

Functions may occur **as data objects**:

- variables
- parameters
- function results
- lambda expressions (in functional languages)

Functions that are defined on the **outermost program level** (non-nested)

can be implemented by just the **address of the code**.

Functions that are **defined in nested structures** have to be implemented by a **pair: (closure, code)**

The **closure** contains all **bindings** of names to variables or values that are valid when the **function definition is executed**.

In **run-time stack** implementations the **closure is a sequence of activation records on the static predecessor chain.**

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3.2 Run-Time Stack Activation Records

Run-time stack contains one **activation record** for each active function call.

Activation record:
provides storage for the data of a function call.

dynamic link:
link from callee to caller,
to the preceding record on the stack

static link:
link from callee c to the record s where c is defined

s is a call of a function which contains the definition of the function, the call of which created c.

Variables of surrounding functions are accessed via the static predecessor chain.

Only relevant for languages which allow **nested functions**, classes, objects.

closure of a function call:
the **activation records on the static predecessor chain**

activation record:

parameters
static link
return address
dynamic link
local variables
register save area

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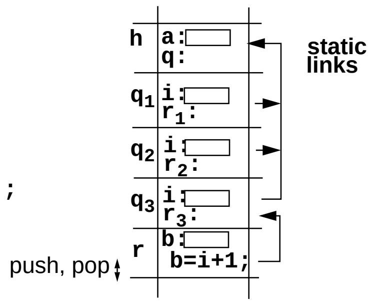
Example for a Run-Time Stack

Run-time stack:
A call creates an activation record and pushes it onto the stack.
It is popped on termination of the call.

nested functions

```
h  float a;
   q  int i;
      r  int b;
         b=i+1;
      if(..) q();
      r();
   q();
```



The **static link** points to the activation record where the called function is defined, e. g. r_3 in q_3

Optimization: activation records of **non-recursive functions** may be allocated statically.

Languages without recursive functions (FORTRAN) do not need a run-time stack.

Parallel processes, threads, and coroutines need a **separate run-time stack** each.

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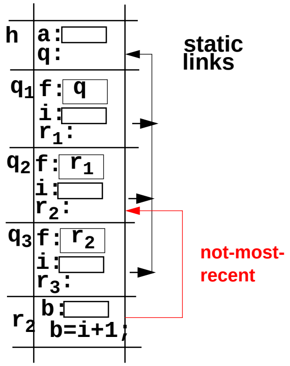
Not-Most-Recent Property

The **static link** of an activation record c for a function r
points to an activation record d for a function q where r is defined in.
If there are activation records for q on the stack, that are more recently created than d,
the **static link to d is not-most-recent**.

That effect can be achieved by using functional parameters or variables.
Example:

nested functions

```
h   float a;

    q(funct f)
      int i;

      r  int b;
         b=i+1;

      if(..) q(r);

      *f();

    q(q);
```



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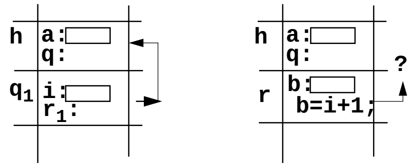
Closures on Run-Time Stacks

Function calls can be implemented by a run-time stack if the

closure of a function is still on the run-time stack when the function is called.

```
h  float a;

   q  int i;

      r  int b;
         b=i+1;

      return r;

   *(q()) ();
```

Example for violation:



during the call of q

the closure for the call of r is missing

Language conditions to guarantee run-time stack discipline:

Pascal:	functions not allowed as function results, or variables
C:	no nested functions
Modula-2:	nested functions not allowed as values of variables

Functional languages maintain activation records on the heap instead of the run-time stack

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Activation Records and Call Code

activation record:

result
parameters
static link
return address
dynamic link
local variables

register save area

\- + 0 base address + -

call code

push parameter values
push static link
subroutine jump

function code

push dynamic link
stack register := top of stack
increment top of stack
for local variables
save registers
...
function body
...
restore registers
deallocate local variables
pop stack register
return jump

pop static link
pop parameter area
use and pop result

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3.3 Code Sequences for Control Statements

A **code sequence** defines how a **control statement** is transformed into jumps and labels.

Notation of the **Code** constructs:

`Code (S)`	generate code for statements **`S`**
`Code (C, true, M)`	generate code for condition **`C`** such that it branches to M if **`C`** is true, otherwise control continues without branching
`Code (A, Ri)`	generate code for expression **`A`** such that the result is in register **`Ri`**

Code sequence for if-else statement:

```
if (cond) ST; else SE;:

          Code (cond, false, M1)
          Code (ST)
          goto M2
    M1:   Code (SE)
    M2:
```

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Short Circuit Translation of Boolean Expressions

Boolean expressions are translated into **sequences of conditional branches**.
Operands are evaluated from left to right until the result is determined.

true
if a or b and c then ST else SE
false

2 code sequences for each operator; applied to condition tree on a top-down traversal:

Code (A and B, true, M): Code (A, false, N)
Code (B, true, M)
N:

Code (A and B, false, M): Code (A, false, M)
Code (B, false, M)

Code (A or B, true, M): Code (A, true, M)
Code (B, true M)

Code (A or B, false, M): Code (A, true, N)
Code (B, false, M)
N:

Code (not A, X, M): Code (A, not X, M)

Code (A < B, true, M): Code (A, Ri);
Code (B, Rj)
cmp Ri, Rj
braLt M

Code (A < B, false, M): Code (A, Ri);
Code (B, Rj)
cmp Ri, Rj
braGe M

Code for a leaf: conditional jump

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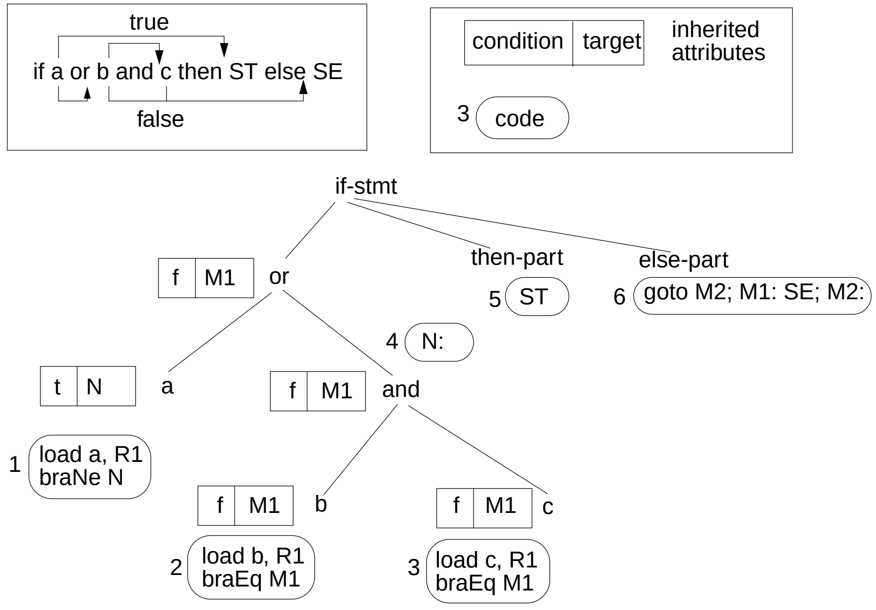
Example for Short Circuit Translation



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Code Sequences for Loops

While-loop variant 1:

```
while (Condition) Body

   M1:  Code (Condition, false, M2)
        Code (Body)
        goto M1
   M2:
```

While-loop variant 2:

```
while (Condition) Body

        goto M2
   M1:  Code (Body)
   M2:  Code (Condition, true, M1)
```

Pascal for-loop unsafe variant:

```
for i:= Init to Final do Body

      i = Init
   L: if (i>Final) goto M
      Code (Body)
      i++
      goto L
   M:
```

Pascal for-loop safe variant:

```
for i:= Init to Final do Body

      if (Init==minint) goto L
      i = Init - 1
      goto N
   L: Code (Body)
   N: if (i>= Final) goto M
      i++
      goto L
   M:
```

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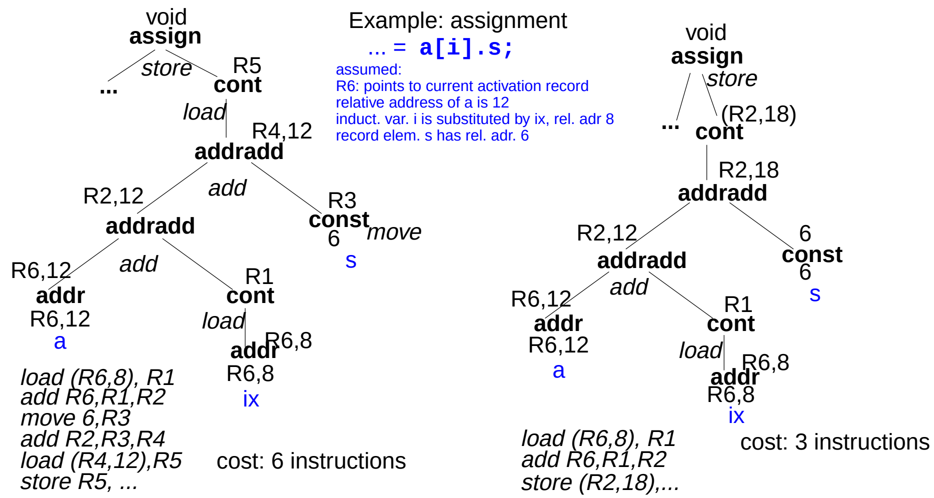
3.4 Code Selection

- Given: target tree in intermediate language.
- **Optimizing selection: Select patterns** that translate single nodes or small subtrees into machine instructions; cover the whole tree with as few instructions as possible.
- Method: **Tree pattern matching,** several techniques



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Selection Technique: Value Descriptors

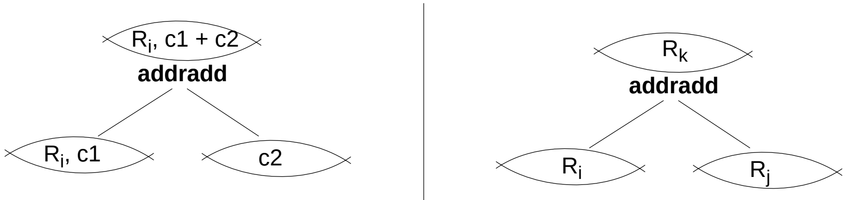
Intermediate language **tree node operators**; e.g.:

addr	address of variable
const	constant value
cont	load contents of address
addradd	address + value

Value descriptors state how/where the value of a tree node is represented, e. g.

$\mathbf{R_i}$	value in register R_i
c	constant value c
$\mathbf{R_{i,c}}$	address R_i + c
(adr)	contents at the address adr

alternative **translation patterns** to be selected context dependend:



addradd R_i, c1 c2 -> R_i, c1 + c2 ./.

addradd R_i R_j -> R_k add R_i, R_j, R_k

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Example for a Set of Translation Patterns

#	operator	operands		result	code
1	**addr**	R_i, c		-> R_i,c	./.
2	**const**	c		-> c	./.
3	**const**	c		-> R_i	move c, R_i
4	**cont**	R_i, c		-> (R_i, c)	./.
5	**cont**	R_i		-> (R_i)	./.
6	**cont**	R_i, c		-> R_j	load (R_i, c), R_j
7	**cont**	R_i		-> R_j	load (R_i), R_j
8	**addradd**	R_i	c	-> R_i, c	./.
9	**addradd**	R_i, c1	c2	-> R_i, c1 + c2	./.
10	**addradd**	R_i	R_j	-> R_k	add Ri, R_j, R_k
11	**addradd**	R_i, c	R_j	-> R_k, c	add R_i, R_j, R_k
12	**assign**	R_i	R_j	-> void	store R_j, R_i
13	**assign**	R_i	(R_j, c)	-> void	store (R_j,c), R_i
14	**assign**	R_i,c	R_j	-> void	store R_j, R_i,c

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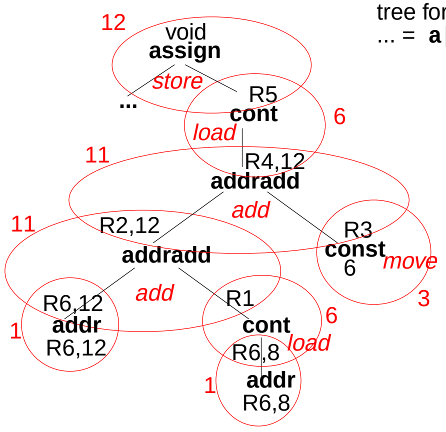
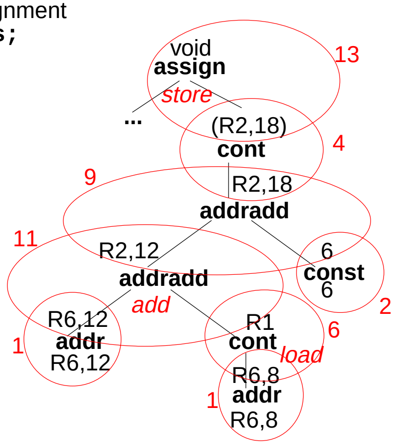
Tree Covered with Translation Patterns

tree for assignment
... = `a[i].s;`



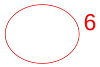
load (R6,8), R1
add R6,R1,R2
move 6,R3
add R2,R3,R4
load (R4,12),R5
store R5, ...

cost: 6 instructions



load (R6,8), R1
add R6,R1,R2
store (R2,18),...

cost: 3 instructions



application of pattern #6

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Pattern Selection

Pass 1 bottom-up:

Annotate the nodes with sets of pairs
{ (v, c) | v is a kind of value descriptor that an applicable pattern yields, c are the accumulated subtree costs}

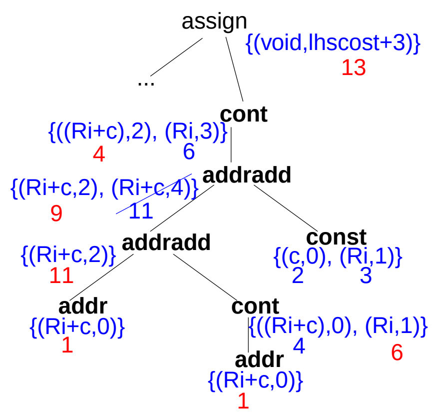
If (v, c1), (v, c2) keep only the cheaper pair.

Pass 2 top-down:

Select for each node the cheapest pattern, that fits to the selection made above.

Pass 3 bottom-up:

Emit code.



load (R6,8), R1
add R6,R1,R2
store (R2,18),...

cost: 3 instructions

Improved technique:

relative costs per sets =>
finite number of potential sets
integer encoding of the sets at generation time

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Pattern Matching in Trees: Bottom-up Rewrite

Bottom-up Rewrite Systems (BURS) :
a general approach of the pattern matching method:

Specification in form of tree patterns, similar to C-3.18 - C-3.20

Set of patterns is **analyzed at generation** time.

Generator produces a **tree automaton** with a finite set of states.

On the bottom-up traversal it annotates each tree node with
a **set of states**:
those selection decisions which may lead to an optimal solution.

Decisions are made on the base of the **costs of subtrees**
rather than costs of nodes.

Generator: BURG

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Tree Pattern Matching by Parsing

The tree is represented in prefix form.

Translation patterns are specified by tuples (CFG production, code, cost),
Value descriptors are the nonterminals of the grammar, e. g.

8	RegConst ::= **addradd** Reg Const	nop	0
11	RegConst ::= **addradd** RegConst Reg	add R_i, R_j, R_k	1

Deeper patterns allow for more effective optimization:

Void ::= **assign** RegConst **addradd** Reg Const	store (Ri, c1),(Rj, c2)	1

Parsing for an ambiguous CFG:
application of a production is decided on the base of the production costs
rather than the accumulated subtree costs!

Technique „Graham, Glanville“
Generators: GG, GGSS

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