Compilers

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Chapter 7:
Intermediate code

Intermediate code (i)

- Why it is useful
  - It facilitates translation
  - It facilitates optimization
  - It facilitates organization in front- and back-end

Intermediate code (ii)

- Syntax-directed translation
  - For each language construct, the corresponding intermediate code is defined
  - The parser is extended with semantic routines for generating the intermediate code

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- Syntax-directed translation
  - For each language construct, the corresponding intermediate code is defined
  - The parser is extended with semantic routines for generating the intermediate code
- Templates for generating intermediate code
- Attributes for each symbol of the grammar

Intermediate representation (i)

- Quadruples

  n: op, x, y, z

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  n: op, x, y, z

- Example:

```
b*b-4*a*c
```

  1: $*$, b, b, \$1
  2: $*$, 4, a, \$2
  3: $*$, \$2, c, \$3
  4: $-$, \$1, \$3, \$4

Intermediate representation (ii)

- Triples

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  n: op, x, y

- Example:

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b*b-4*a*c
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  2: $*$, 4, a
  3: $*$, (2), c
  4: $-$, (1), (3)

Intermediate representation (iii)

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- Example:

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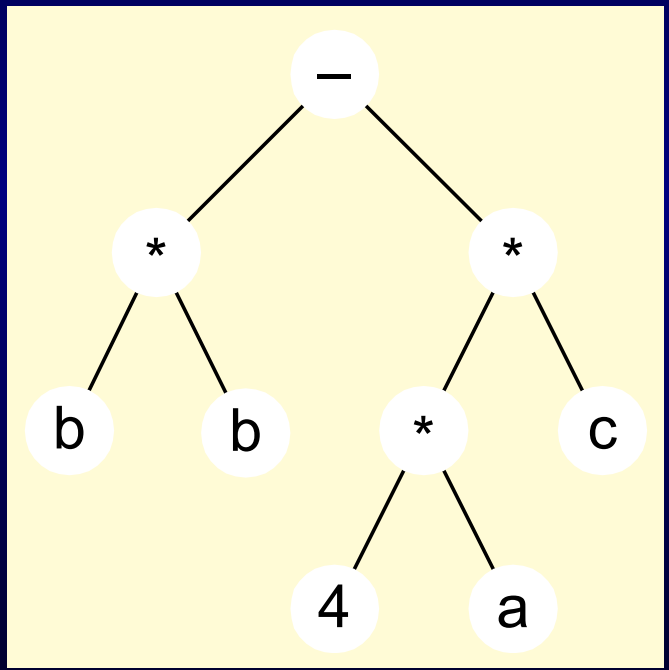
```



Intermediate representation (iv)

- Prefix and postfix code

Intermediate representation (iv)

- Prefix and postfix code
- Example: `b*b-4*a*c`

  $- * b\ b * * 4\ a\ c$ prefix

  $b\ b * 4\ a * c * -$ postfix

Intermediate representation (v)

- Directed acyclic graphs

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- Example:

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b+(a+1)*(a+1)+c-(a+1)*(a+1)+2/(a+1)
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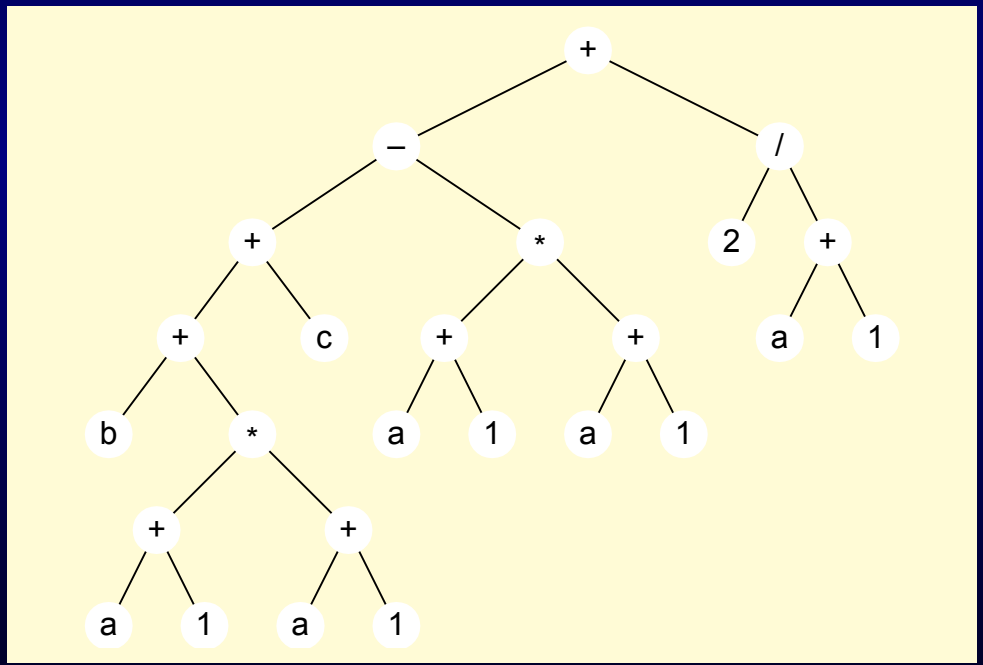

Intermediate representation (v)

- Directed acyclic graphs
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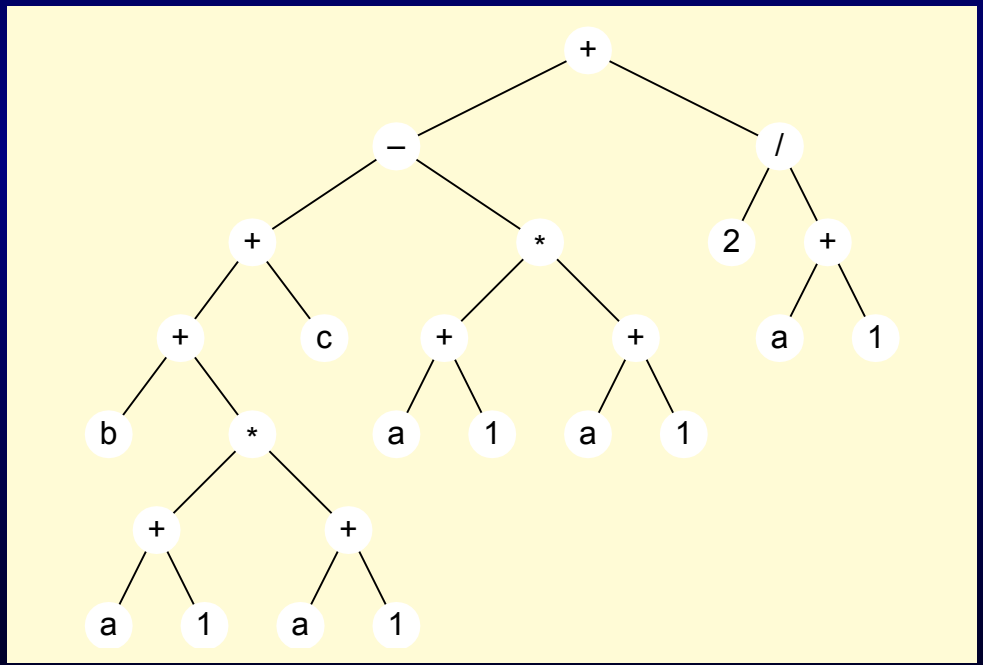
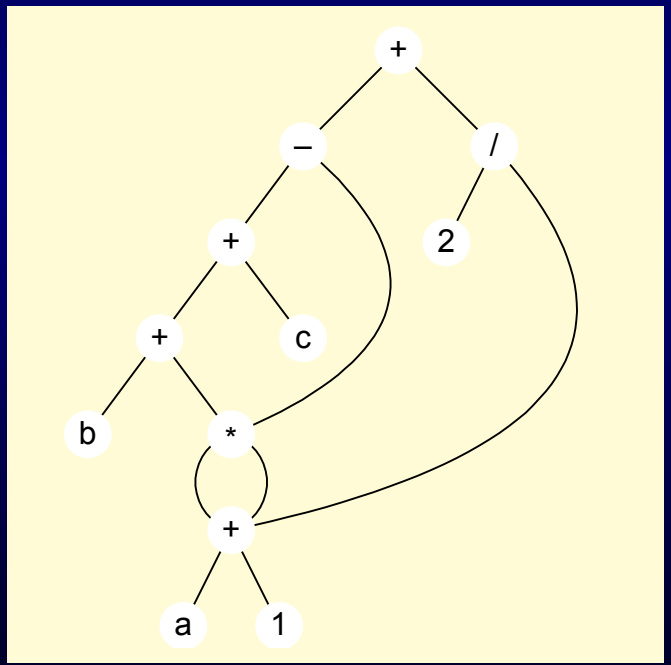




The language of quadruples

- Form of a quadruple:

  n: op, x, y, z

  where:

  - n: label (a natural number)
  - op: operator
  - x, y, z: operands
- For different types of operators, some operands may be ommitted

Operands (i)

- Constant
  - integer, real, boolean
  - character, string, `nil`
- Name
  - variable, parameter, subprogram
- Temporary variable: $$n
- Function result: $$
- Dereference: $[x]$ — x simple operand
- Address: $\{x\}$ — x simple operand

Operands (ii)

- Label
  - of a statement in the source code
  - of a label
- Parameter passing mode
  - V : by value
  - R : by reference
  - RET : address of function result
- Blank : —
- Temporarily blank : * (for backpatching)

Operators (i)

- unit, I, $-$, $-$
- endu, I, $-$, $-$
  beginning and end of a program unit
- op, x, y, z $\qquad op \in \{+, -, *, /, \%\}$
  $z := x \; op \; y$
- $:=, x, -, z$
  $z := x$
- array, x, y, z
  $z :=$ the address of element $x[y]$

Operators (ii)

- op, x, y, z $\quad op \in \{=, <>, >, <, >=, <=\}$
  if x *op* y then jump to quadruple z
- ifb, x, $-$, z
  if the boolean value x is true then jump to quadruple z
- jump, $-$, $-$, z
  jump to quadruple z
- label, I, $-$, $-$
  jumpl, $-$, $-$, I
  define a label and jump to that

Operators (iii)

- call, –, –, I
  call the program unit I
- par, x, m, –
  pass the actual parameter x using passing mode m
- ret, –, –, –
  return from the current program unit

Attributes used in intermediate code

- *PLACE*: the place where an l-value or r-value is stored
- *TYPE*: the type of an l-value or r-value
- *NEXT*: the list of quadruple labels that contain jumps to the next statement
- *TRUE, FALSE*: lists of labels containing jumps to the code that must be executed if a condition is true or false

Auxiliary routines (i)

- NEXTQUAD()
  Returns the number of the next quadruple
- GENQUAD(op, x, y, z)
  Generates the next quadruple op, x, y, z
- NEWTEMP(t)
  Generates a new temporary variable of type t
- EMPTYLIST()
  Generates an empty list of quadruple labels

Auxiliary routines (ii)

- MAKELIST(x)
  Generates a list of quadruple labels containing just the element x
- MERGE$(l_1, \ldots, l_n)$
  Merges the list of quadruple labels $l_1 \ldots l_n$
- BACKPATCH(l, z)
  Replaces in all quadruples whose labels are contained in l the unknown quadruple label (last operand) with z (backpatching)

Arithmetic expressions

- Numerical constants

  $\langle \text{r-value} \rangle \ ::= \ \langle \text{integer-const} \rangle \ \{ P_1 \}$

  $P_1 \quad : \quad \{ \ \langle \text{r-value} \rangle .PLACE = \langle \text{integer-const} \rangle ; \ \}$

Arithmetic expressions

- Numerical constants

$\langle$r-value$\rangle$ ::= $\langle$integer-const$\rangle$ $\{ P_1 \}$

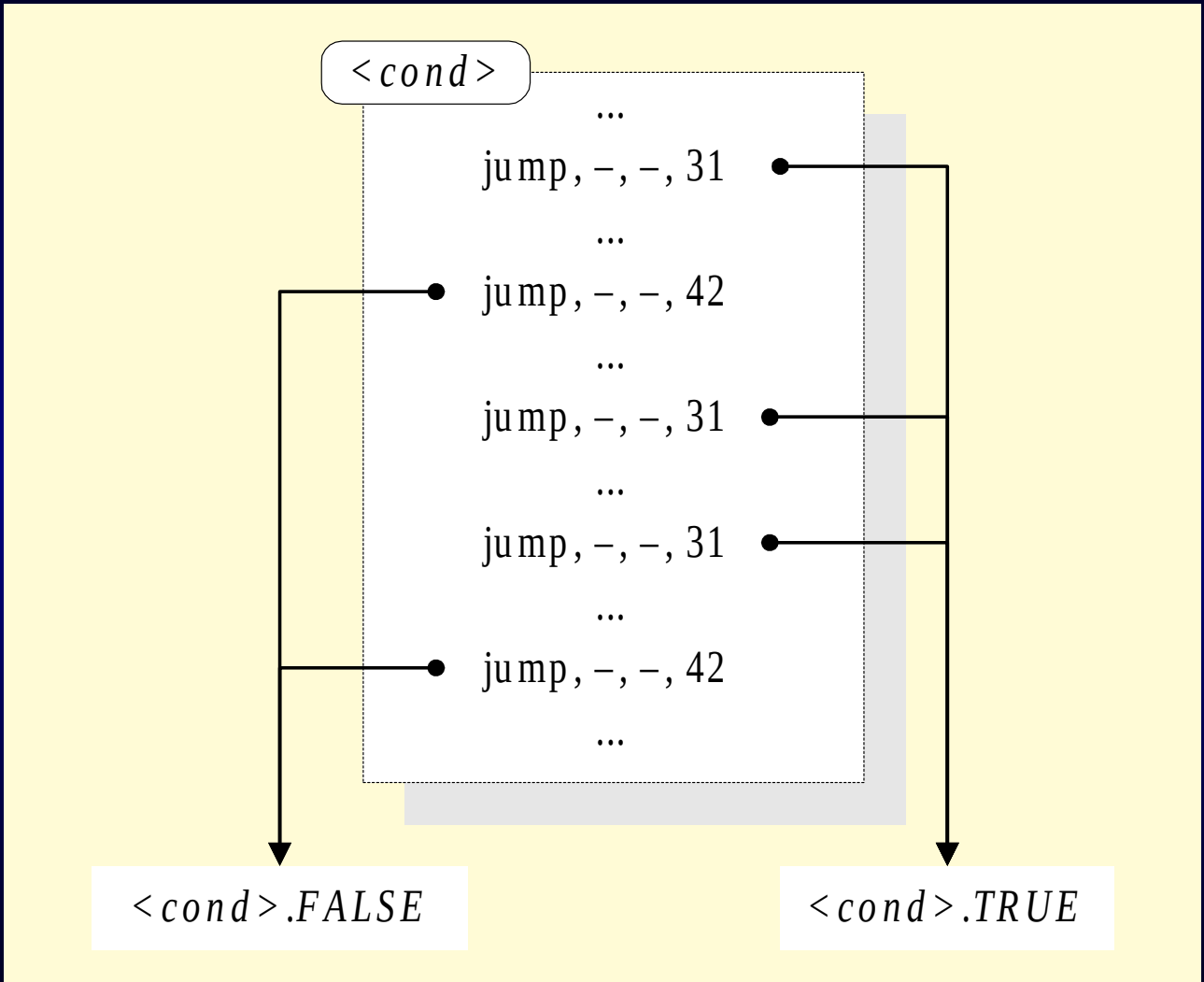
P_1 : $\{$ $\langle$r-value$\rangle$.*PLACE* = $\langle$integer-const$\rangle$; $\}$

- Binary operators

$\langle$r-value$\rangle$ ::= $\langle$expr$\rangle$ $\langle$binop$\rangle$ $\langle$expr$\rangle$ $\{ P_{14} \}$

P_{14} : $\{$ W = NEWTEMP($\langle$r-value$\rangle$.*TYPE*);
GENQUAD($\langle$binop$\rangle$.*NAME*,
$\langle$expr$\rangle^1$.*PLACE*,
$\langle$expr$\rangle^2$.*PLACE*, W);
$\langle$r-value$\rangle$.*PLACE* = W; $\}$

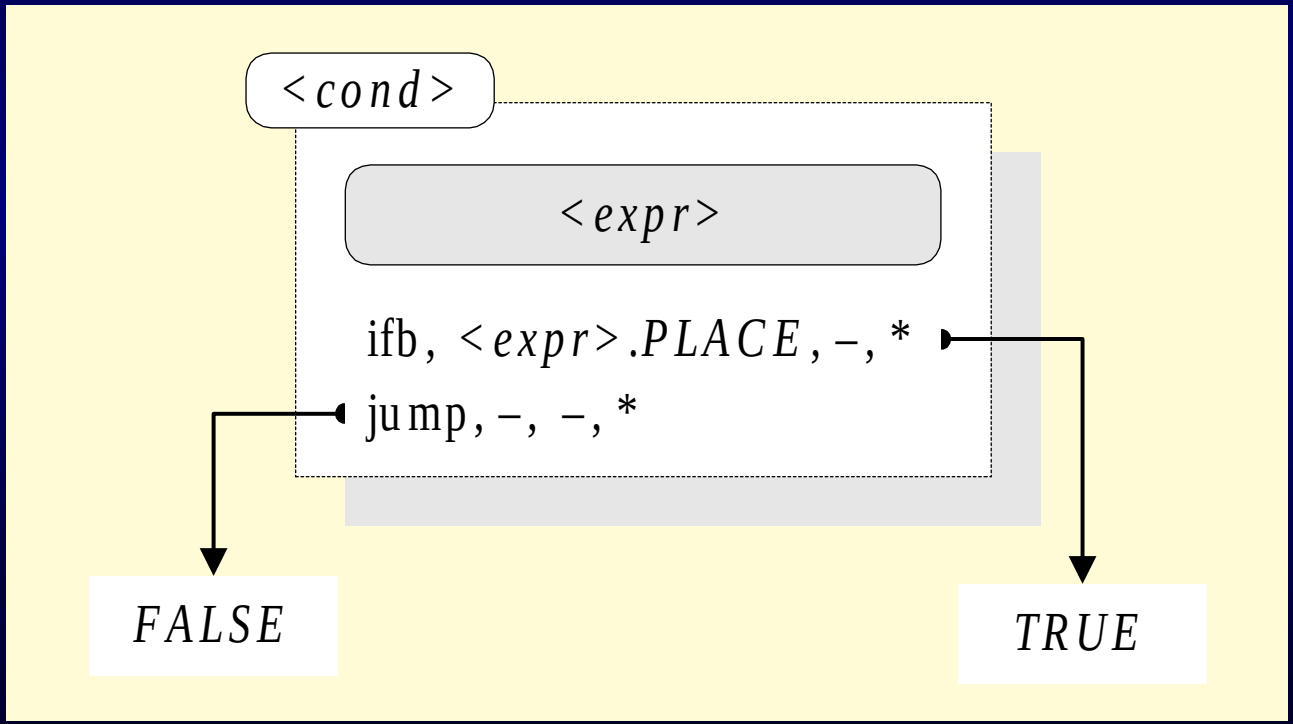
Conditions (i)



Conditions (ii)

- Conditions represented as 0/1

  ⟨cond⟩ ::= ⟨expr⟩



Conditions (iii)

- Conditions represented as 0/1

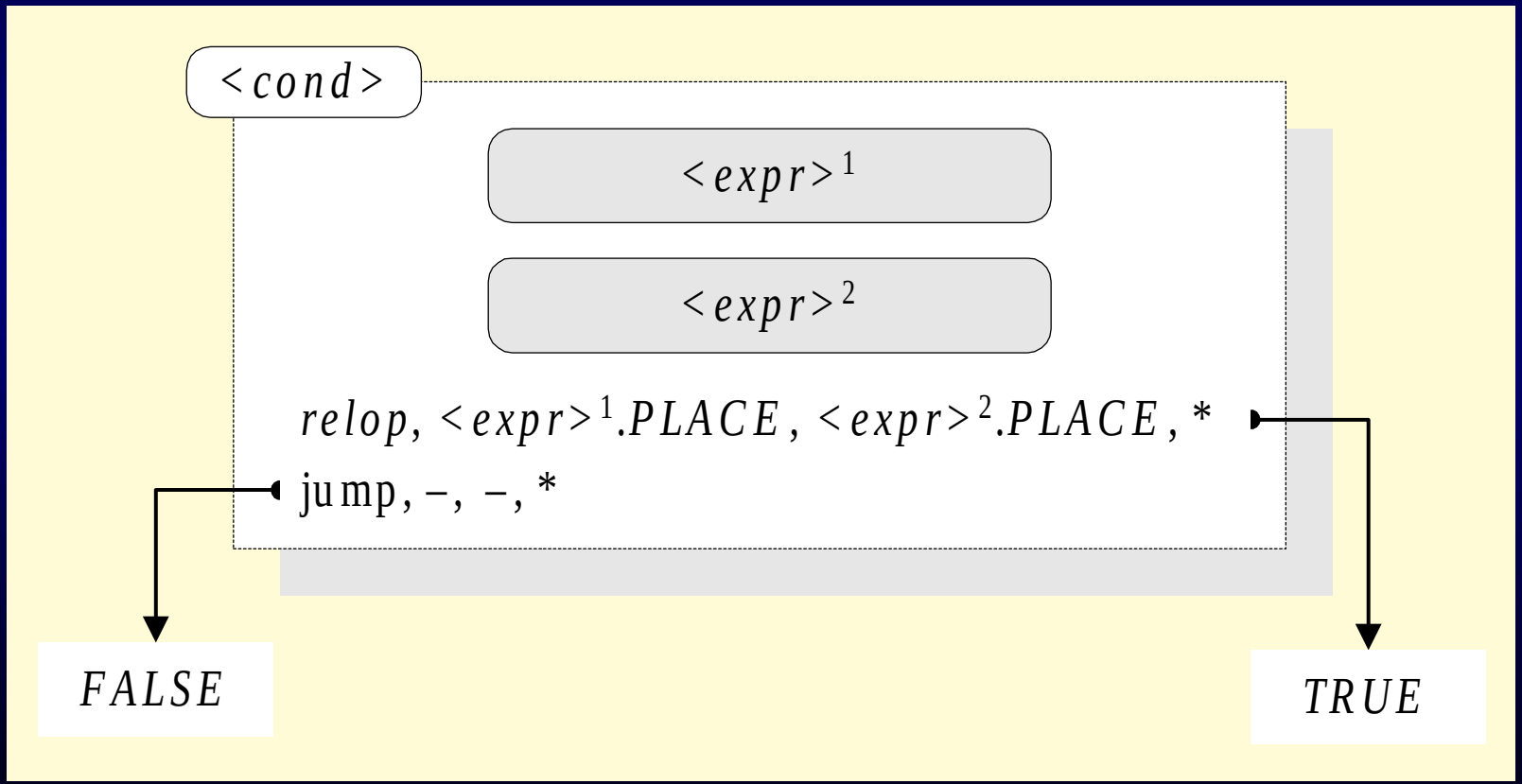
$$\langle \text{cond} \rangle \ ::= \ \langle \text{expr} \rangle \ \{ P_{21} \}$$

$$P_{21} \ : \ \{ \ \langle \text{cond} \rangle .\mathit{TRUE} = \text{MAKELIST}(\text{NEXTQUAD}());$$
$$\text{GENQUAD}(\text{ifb}, \langle \text{expr} \rangle .\mathit{PLACE}, -, *);$$
$$\langle \text{cond} \rangle .\mathit{FALSE} = \text{MAKELIST}(\text{NEXTQUAD}());$$
$$\text{GENQUAD}(\text{jump}, -, -, *); \ \ \}$$

Conditions (iv)

- Arithmetic comparisons

$\langle \text{cond} \rangle ::= \langle \text{expr} \rangle^1 \ \langle \text{relop} \rangle \ \langle \text{expr} \rangle^2$



Conditions (v)

- Arithmetic comparisons

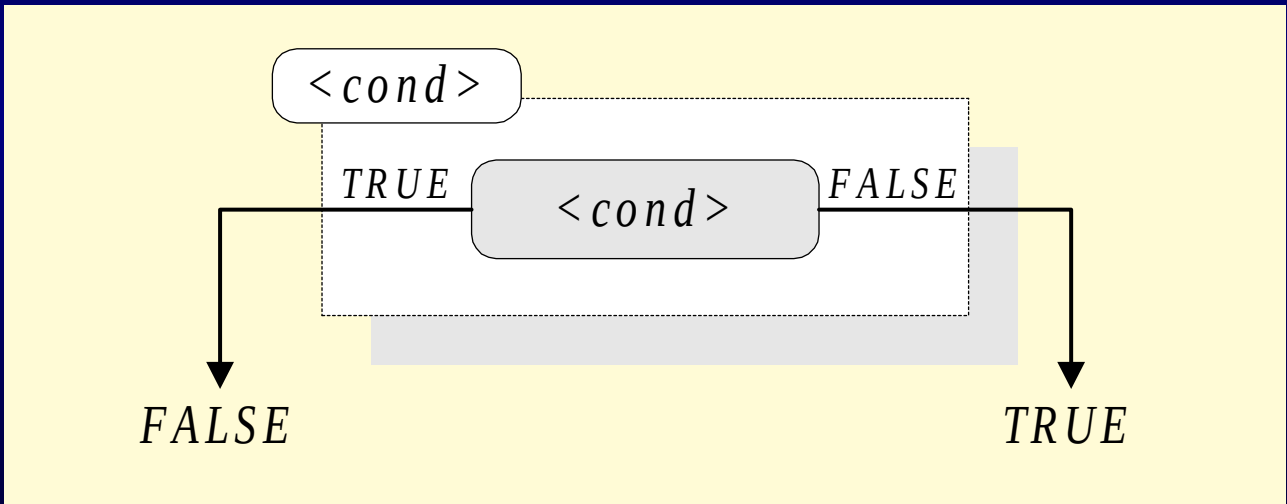
$$\langle \text{cond} \rangle ::= \langle \text{expr} \rangle^1 \ \langle \text{relop} \rangle \ \langle \text{expr} \rangle^2 \ \{ P_{23} \}$$

$$\begin{aligned} P_{23} : \{ \ & \langle \text{cond} \rangle .\mathit{TRUE} = \text{MAKELIST}(\text{NEXTQUAD}()); \\ & \text{GENQUAD}(\langle \text{relop} \rangle .\mathit{NAME}, \\ & \qquad \langle \text{expr} \rangle^1 .\mathit{PLACE}, \\ & \qquad \langle \text{expr} \rangle^2 .\mathit{PLACE}, *); \\ & \langle \text{cond} \rangle .\mathit{FALSE} = \text{MAKELIST}(\text{NEXTQUAD}()); \\ & \text{GENQUAD}(\text{jump}, -, -, *); \ \} \end{aligned}$$

Conditions (vi)

- Negation

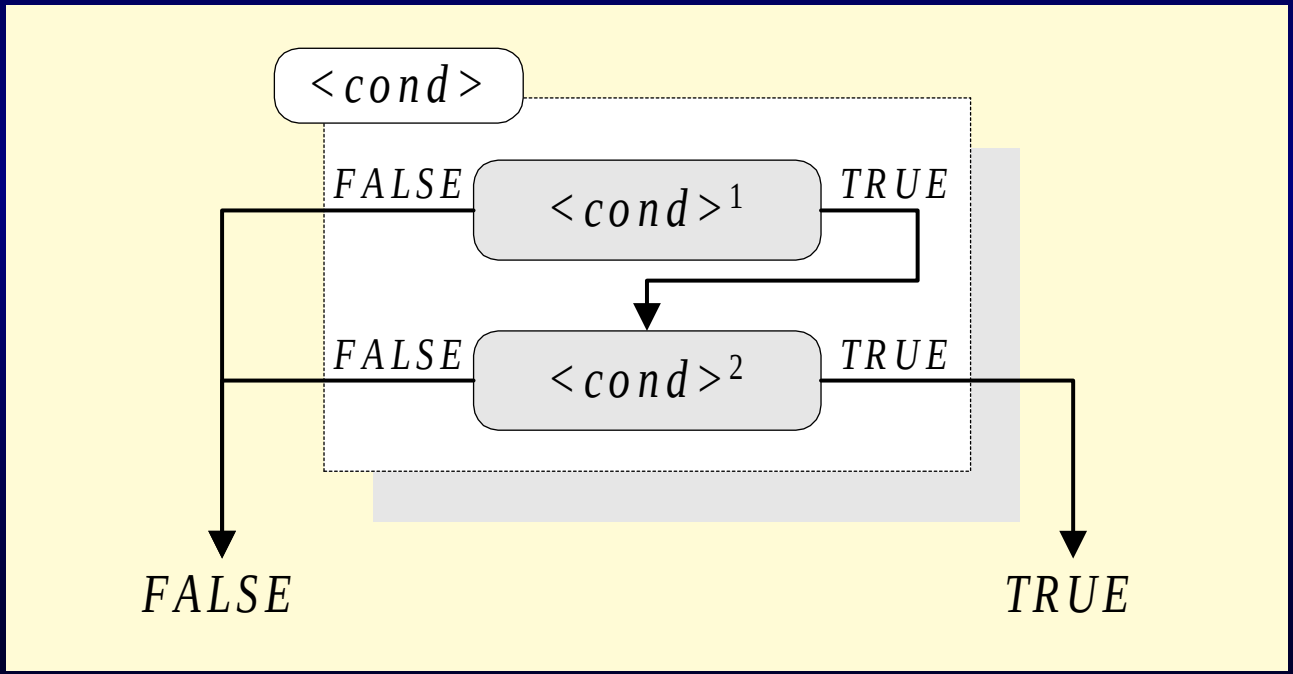
  ⟨cond⟩ ::= “**not**” ⟨cond⟩



Conditions (vii)

- Conjunction

  $\langle \text{cond} \rangle ::= \langle \text{cond} \rangle^1$ “**and**” $\langle \text{cond} \rangle^2$



Conditions (viii)

- Conjunction

$$\langle \text{cond} \rangle ::= \langle \text{cond} \rangle_1 \text{ “}\textbf{and}\text{” } \{ P_{25} \} \langle \text{cond} \rangle_2 \{ P_{26} \}$$

$$P_{25} : \{ \text{BACKPATCH}(\langle \text{cond} \rangle^1 .\mathit{TRUE}, \text{NEXTQUAD}()); \}$$

$$P_{26} : \{ \langle \text{cond} \rangle .\mathit{FALSE} = \text{MERGE}(\langle \text{cond} \rangle^1 .\mathit{FALSE}, \langle \text{cond} \rangle^2 .\mathit{FALSE}); \langle \text{cond} \rangle .\mathit{TRUE} = \langle \text{cond} \rangle^2 .\mathit{TRUE}; \}$$

Simple statements

- The empty statement

$$\langle \text{stmt} \rangle \ ::= \ \epsilon \ \{ P_{29} \}$$
$$P_{29} \ : \ \{ \ \langle \text{stmt} \rangle .NEXT = \text{EMPTYLIST}(); \ \}$$

Simple statements

- The empty statement

$\langle \text{stmt} \rangle \ ::= \ \epsilon \ \{ P_{29} \}$

$P_{29} \ : \ \{ \ \langle \text{stmt} \rangle .NEXT = \text{EMPTYLIST}(); \ \}$

- Assignment

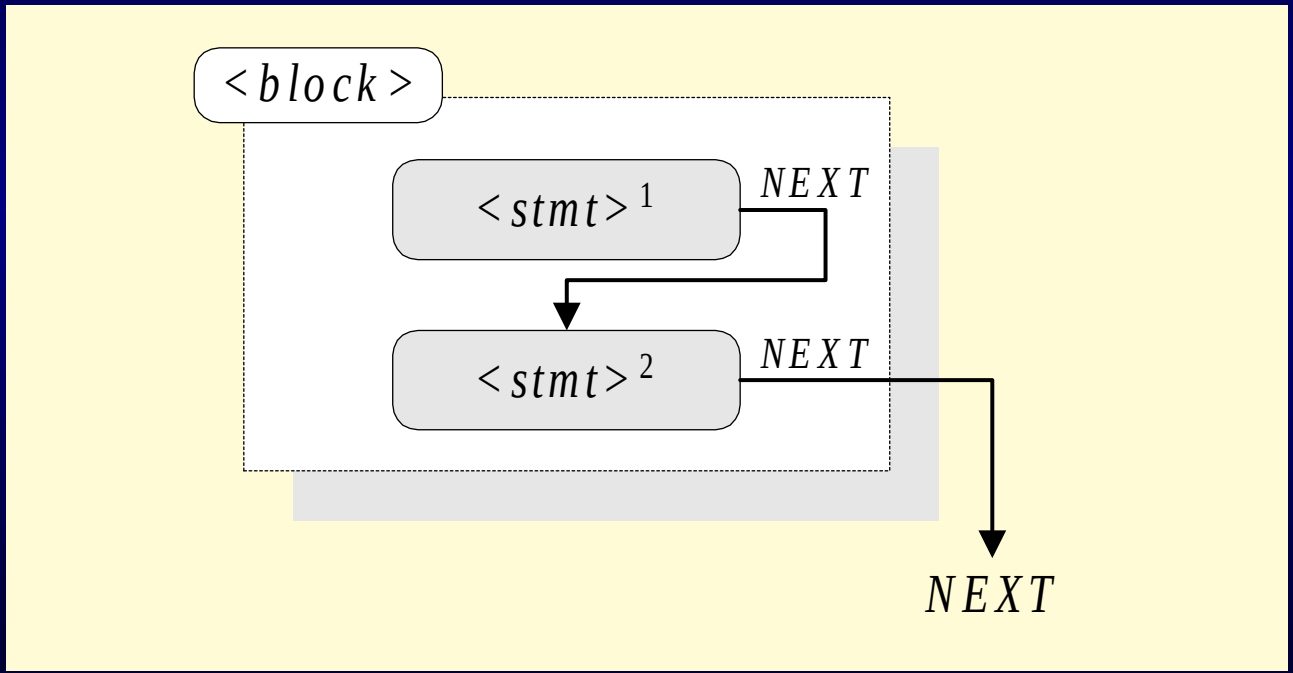
$\langle \text{stmt} \rangle \ ::= \ \langle \text{l-value} \rangle \ \text{“:=”} \ \langle \text{expr} \rangle \ \{ P_{30} \}$

$P_{30} \ : \ \{ \ \text{GENQUAD}(\text{“:=”}, \langle \text{expr} \rangle .PLACE, -, \langle \text{l-value} \rangle .PLACE);$
$\langle \text{stmt} \rangle .NEXT = \text{EMPTYLIST}(); \ \}$

Compound statement (i)

⟨stmt⟩ ::= ⟨block⟩

⟨block⟩ ::= “**begin**” ⟨stmt⟩ (“;” ⟨stmt⟩)* “**end**”



Compound statement (ii)

$\langle \text{stmt} \rangle$ ::= $\langle \text{block} \rangle$ $\{ P_{34} \}$

P_{34} : $\{ \langle \text{stmt} \rangle .NEXT = \langle \text{block} \rangle .NEXT; \}$

$\langle \text{block} \rangle$ ::= "**begin**" $\langle \text{stmt} \rangle^1$ $\{ P_{35} \}$
(";" $\{ P_{36} \}$ $\langle \text{stmt} \rangle^2$ $\{ P_{37} \}$)* "**end**" $\{ P_{38} \}$

P_{35} : $\{ L = \langle \text{stmt} \rangle^1 .NEXT; \}$

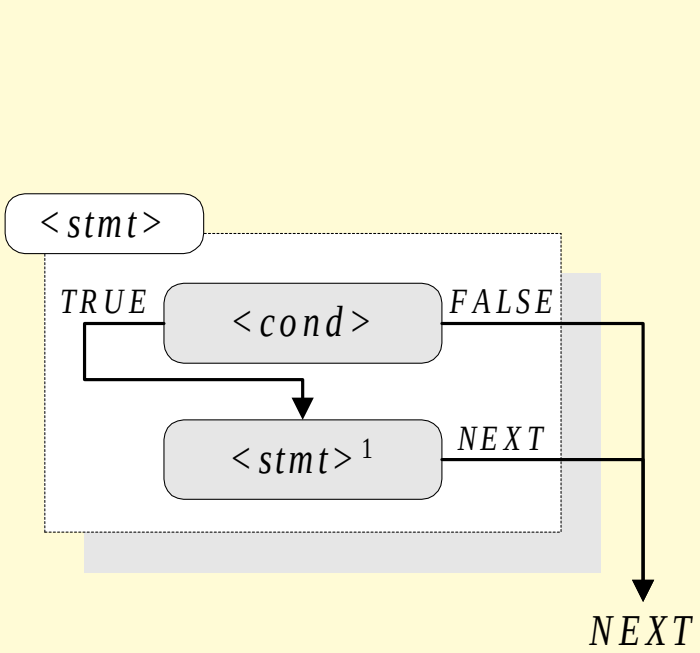
P_{36} : $\{ \text{BACKPATCH}(L, \text{NEXTQUAD}()); \}$

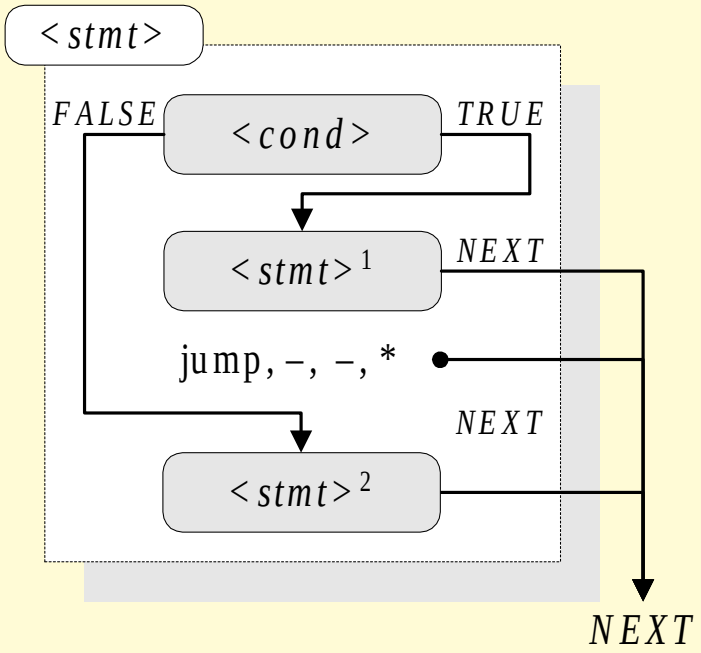
P_{37} : $\{ L = \langle \text{stmt} \rangle^2 .NEXT; \}$

P_{38} : $\{ \langle \text{block} \rangle .NEXT = L; \}$

If statement (i)

⟨stmt⟩ ::= **“if”** ⟨cond⟩ **“then”** ⟨stmt⟩ [**“else”** ⟨stmt⟩]





If statement (ii)

$$\langle \text{stmt} \rangle ::= \text{“}\textbf{if}\text{”}\ \langle \text{cond} \rangle\ \{ P_{39} \}\ \text{“}\textbf{then}\text{”}\ \langle \text{stmt} \rangle^1\ [\ \text{“}\textbf{else}\text{”}\ \{ P_{40} \}\ \langle \text{stmt} \rangle^2\ \{ P_{41} \}\ ]\ \{ P_{42} \}$$

$$P_{39} : \{\ \text{BACKPATCH}(\langle \text{cond} \rangle.\mathit{TRUE}, \text{NEXTQUAD}());\ L_1 = \langle \text{cond} \rangle.\mathit{FALSE};\ L_2 = \text{EMPTYLIST}();\ \}$$

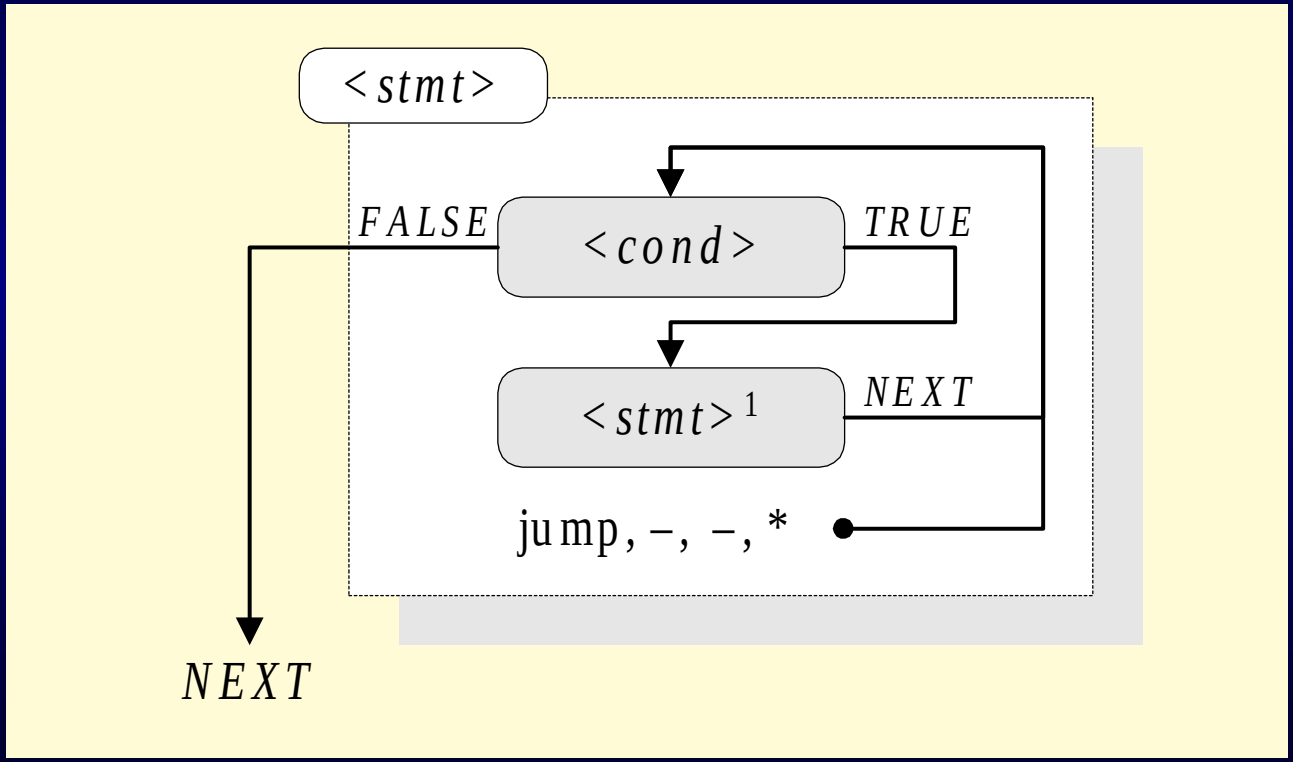
$$P_{40} : \{\ L_1 = \text{MAKELIST}(\text{NEXTQUAD}());\ \text{GENQUAD}(\text{jump}, -, -, *);\ \text{BACKPATCH}(\langle \text{cond} \rangle.\mathit{FALSE}, \text{NEXTQUAD}());\ \}$$

$$P_{41} : \{\ L_2 = \langle \text{stmt} \rangle^2.\mathit{NEXT};\ \}$$

$$P_{42} : \{\ \langle \text{stmt} \rangle.\mathit{NEXT} = \text{MERGE}(L_1, \langle \text{stmt} \rangle^1.\mathit{NEXT}, L_2);\ \}$$

While statement (i)

⟨stmt⟩ ::= “**while**” ⟨cond⟩ “**do**” ⟨stmt⟩



While statement (ii)

$$\langle \text{stmt} \rangle ::= \text{“}\textbf{while}\text{”}\ \{ P_{43} \}\ \langle \text{cond} \rangle\ \text{“}\textbf{do}\text{”}\ \{ P_{44} \}\ \langle \text{stmt} \rangle^1\ \{ P_{45} \}$$

$$P_{43} : \{\ Q = \text{NEXTQUAD}();\ \}$$

$$P_{44} : \{\ \text{BACKPATCH}(\langle \text{cond} \rangle .\mathit{TRUE}, \text{NEXTQUAD}());\ \}$$

$$P_{45} : \{\ \text{BACKPATCH}(\langle \text{stmt} \rangle^1 .\mathit{NEXT}, Q);$$
$$\text{GENQUAD}(\text{jump}, -, -, Q);$$
$$\langle \text{stmt} \rangle .\mathit{NEXT} = \langle \text{cond} \rangle .\mathit{FALSE};\ \}$$

Subprogram calls (i)

⟨call⟩ ::= ⟨id⟩ “(” [⟨expr⟩ (“,” ⟨expr⟩)*] “)”
⟨r-value⟩ ::= ⟨call⟩
⟨stmt⟩ ::= ⟨call⟩

- Parameter passing, using `par` quadruples
- Address of result, using an extra `par` quadruple, if it is a function
- Call, using a `call` quadruple

Subprogram calls (ii)

$$
\begin{aligned}
\langle \text{call} \rangle \ ::= \ & \langle \text{id} \rangle \ \text{“(”} \ \{ P_{46} \} \ [\ \langle \text{expr} \rangle^1 \ \{ P_{47} \} \\
& (\ \text{“,”} \ \langle \text{expr} \rangle^2 \ \{ P_{48} \} \ )^* \ ] \ \text{“)”} \ \{ P_{49} \} \\
P_{46} \ : \ & \{ \ N = 1; \ \} \\
P_{47} \ : \ & \{ \ \text{GENQUAD}(\text{“}\textbf{par}\text{”}, \langle \text{expr} \rangle^1 .\mathit{PLACE}, \\
& \qquad \text{PARAMMODE}(\langle \text{id} \rangle, N), -); \\
& \ N = N + 1; \ \} \\
P_{48} \ : \ & \{ \ \text{GENQUAD}(\text{“}\textbf{par}\text{”}, \langle \text{expr} \rangle^2 .\mathit{PLACE}, \\
& \qquad \text{PARAMMODE}(\langle \text{id} \rangle, N), -); \\
& \ N = N + 1; \ \}
\end{aligned}
$$

Subprogram calls (iii)

$\langle \text{call} \rangle$ ::= $\langle \text{id} \rangle$ “(” $\{P_{46}\}$ [$\langle \text{expr} \rangle^1$ $\{P_{47}\}$
(“,” $\langle \text{expr} \rangle^2$ $\{P_{48}\}$)*] “)” $\{P_{49}\}$

(continued)

P_{49} : { **if** (ISFUNCTION($\langle \text{id} \rangle$)) {
W = NEWTEMP(FUNCRESULT($\langle \text{id} \rangle$));
GENQUAD(par, RET, W, −);
$\langle \text{call} \rangle$.*PLACE* = W;
}
GENQUAD(call, −, −, $\langle \text{id} \rangle$); }

Subprogram calls (iv)

- Function call

  $\langle$r-value$\rangle$ ::= $\langle$call$\rangle$ $\{ P_{50} \}$

  P_{50} : $\{$ $\langle$r-value$\rangle$.*PLACE* = $\langle$call$\rangle$.*PLACE*; $\}$

Subprogram calls (iv)

- Function call

  $\langle$r-value$\rangle$ ::= $\langle$call$\rangle$ $\{ P_{50} \}$

  P_{50} : $\{$ $\langle$r-value$\rangle$.*PLACE* = $\langle$call$\rangle$.*PLACE*; $\}$

- Procedure call

  $\langle$stmt$\rangle$ ::= $\langle$call$\rangle$ $\{ P_{51} \}$

  P_{51} : $\{$ $\langle$stmt$\rangle$.*NEXT* = EMPTYLIST(); $\}$

Subprogram call (v)

- Return from a subprogram

$\langle \text{stmt} \rangle ::= \text{“}\textbf{return}\text{”} \; [\; \langle \text{expr} \rangle \; \{ P_{52} \} \;] \; \{ P_{53} \}$

$P_{52} : \{ \; \text{GENQUAD}(\text{retv}, \langle \text{expr} \rangle .PLACE, -, -); \; \}$

$P_{53} : \{ \; \text{GENQUAD}(\text{ret}, -, -, -); \; \}$

Subprogram call (v)

- Return from a subprogram

  $\langle \text{stmt} \rangle$ ::= "**return**" [$\langle \text{expr} \rangle$ { P_{52} }] { P_{53} }

  P_{52} : { GENQUAD(retv, $\langle \text{expr} \rangle$.*PLACE*, −, −); }

  P_{53} : { GENQUAD(ret, −, −, −); }

- Subprogram definition

  $\langle \text{body} \rangle$ ::= ($\langle \text{local} \rangle$)* { P_{56} } $\langle \text{block} \rangle$ ";" { P_{57} }

  P_{56} : { GENQUAD(unit, I, −, −); }

  P_{57} : { BACKPATCH($\langle \text{block} \rangle$.*NEXT*, NEXTQUAD());
  GENQUAD(endu, I, −, −); }

Example (i)

```
procedure quicksort (var a : array of integer;
                     m, n : integer);
   var i, j, temp : integer;
begin
  if n <= m then return;
  i := m; j := n;
  while i <= j do begin
    while a[i] < a[(m+n) div 2] do i := i+1;
    while a[j] > a[(m+n) div 2] do j := j-1;
    if i <= j then begin
      temp := a[i]; a[i] := a[j]; a[j] := temp;
      i := i+1; j := j-1
    end
  end;
  quicksort(a, m, j); quicksort(a, i, n)
end;
```

Example (ii)

```
procedure quicksort (var a : array of integer;
                     m, n : integer);
   var i, j, temp : integer;
begin
  if n <= m then return;
  i := m; j := n;
```

Example (ii)

```
procedure quicksort (var a : array of integer;
                     m, n : integer);
   var i, j, temp : integer;
begin
  if n <= m then return;
  i := m; j := n;
```

1: unit, quicksort, —, —

Example (ii)

```
procedure quicksort (var a : array of integer;
                     m, n : integer);
   var i, j, temp : integer;
begin
  if n <= m then return;
  i := m; j := n;
```

1: unit, quicksort, —, —
2: <=, n, m, *

Example (ii)

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procedure quicksort (var a : array of integer;
                     m, n : integer);
   var i, j, temp : integer;
begin
  if n <= m then return;
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```

1: unit, quicksort, —, —
2: <=, n, m, *
3: jump, —, —, *

Example (ii)

```
procedure quicksort (var a : array of integer;
                     m, n : integer);
   var i, j, temp : integer;
begin
  if n <= m then return;
  i := m; j := n;
```

1: unit, quicksort, —, —
2: $<=$, n, m, $*$
3: jump, —, —, $*$
4: ret, —, —, —

Example (ii)

```
procedure quicksort (var a : array of integer;
                     m, n : integer);
   var i, j, temp : integer;
begin
  if n <= m then return;
  i := m; j := n;
```

1: unit, quicksort, —, —
2: <=, n, m, 4
3: jump, —, —, *
4: ret, —, —, —

Example (ii)

```
procedure quicksort (var a : array of integer;
                     m, n : integer);
   var i, j, temp : integer;
begin
  if n <= m then return;
  i := m; j := n;
```

1: unit, quicksort, —, —
2: <=, n, m, 4
3: jump, —, —, 5
4: ret, —, —, —

Example (ii)

```
procedure quicksort (var a : array of integer;
                     m, n : integer);
   var i, j, temp : integer;
begin
  if n <= m then return;
  i := m; j := n;
```

1: unit, quicksort, —, —
2: <=, n, m, 4
3: jump, —, —, 5
4: ret, —, —, —
5: :=, m, —, i

Example (ii)

```
procedure quicksort (var a : array of integer;
                     m, n : integer);
   var i, j, temp : integer;
begin
  if n <= m then return;
  i := m; j := n;
```

1: unit, quicksort, −, −
2: <=, n, m, 4
3: jump, −, −, 5
4: ret, −, −, −
5: :=, m, −, i
6: :=, n, −, j

Example (iii)

```
while i <= j do begin
  while a[i] < a[(m+n) div 2] do i := i+1;
  while a[j] > a[(m+n) div 2] do j := j-1;
```

Example (iii)

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while i <= j do begin
  while a[i] < a[(m+n) div 2] do i := i+1;
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```

7: $<=, \mathrm{i}, \mathrm{j}, *$

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while i <= j do begin
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7: $<=, \mathrm{i}, \mathrm{j}, *$

8: $\mathrm{jump}, -, -, *$

Example (iii)

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while i <= j do begin
  while a[i] < a[(m+n) div 2] do i := i+1;
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7: $<=, \mathrm{i}, \mathrm{j}, 9$

8: $\mathrm{jump}, -, -, *$

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  while a[i] < a[(m+n) div 2] do i := i+1;
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7: $<=, \mathrm{i}, \mathrm{j}, 9$

8: $\mathrm{jump}, -, -, *$

9: $\mathrm{array}, \mathrm{a}, \mathrm{i}, \$1$

Example (iii)

```
while i <= j do begin
  while a[i] < a[(m+n) div 2] do i := i+1;
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7: $<=, \mathrm{i}, \mathrm{j}, 9$
8: $\mathrm{jump}, -, -, *$
9: $\mathrm{array}, \mathrm{a}, \mathrm{i}, \$1$
10: $+, \mathrm{m}, \mathrm{n}, \$2$

Example (iii)

```
while i <= j do begin
  while a[i] < a[(m+n) div 2] do i := i+1;
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```

7: $<=, \text{i}, \text{j}, 9$
8: $\text{jump}, -, -, *$
9: $\text{array}, \text{a}, \text{i}, \$1$
10: $+, \text{m}, \text{n}, \$2$
11: $/, \$2, 2, \$3$

Example (iii)

```
while i <= j do begin
  while a[i] < a[(m+n) div 2] do i := i+1;
  while a[j] > a[(m+n) div 2] do j := j-1;
```

7: $<=$, i, j, 9
8: jump, $-$, $-$, $*$
9: array, a, i, \$1
10: $+$, m, n, \$2
11: $/$, \$2, 2, \$3
12: array, a, \$3, \$4

Example (iii)

```
while i <= j do begin
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7: $<=, \text{i}, \text{j}, 9$
8: $\text{jump}, -, -, *$
9: $\text{array}, \text{a}, \text{i}, \$1$
10: $+, \text{m}, \text{n}, \$2$
11: $/, \$2, 2, \$3$
12: $\text{array}, \text{a}, \$3, \$4$
13: $<, [\$1], [\$4], *$

Example (iii)

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while i <= j do begin
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9: $\text{array}, \text{a}, \text{i}, \$1$
10: $+, \text{m}, \text{n}, \$2$
11: $/, \$2, 2, \$3$
12: $\text{array}, \text{a}, \$3, \$4$
13: $<, [\$1], [\$4], *$
14: $\text{jump}, -, -, *$

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8: $\text{jump}, -, -, *$
9: $\text{array}, \text{a}, \text{i}, \$1$
10: $+, \text{m}, \text{n}, \$2$
11: $/, \$2, 2, \$3$
12: $\text{array}, \text{a}, \$3, \$4$
13: $<, [\$1], [\$4], 15$
14: $\text{jump}, -, -, *$

Example (iii)

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while i <= j do begin
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  while a[j] > a[(m+n) div 2] do j := j-1;
```

7: $<=$, i, j, 9
8: jump, $-$, $-$, $*$
9: array, a, i, \$1
10: $+$, m, n, \$2
11: $/$, \$2, 2, \$3
12: array, a, \$3, \$4
13: $<$, [\$1], [\$4], 15
14: jump, $-$, $-$, $*$
15: $+$, i, 1, \$5

Example (iii)

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while i <= j do begin
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7: $<=, \text{i}, \text{j}, 9$
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13: $<, [\$1], [\$4], 15$
14: $\text{jump}, -, -, *$
15: $+, \text{i}, 1, \$5$
16: $:=, \$5, -, \text{i}$

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12: $\text{array}, \text{a}, \$3, \$4$
13: $<, [\$1], [\$4], 15$
14: $\text{jump}, -, -, *$
15: $+, \text{i}, 1, \$5$
16: $:=, \$5, -, \text{i}$
17: $\text{jump}, -, -, 9$

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9: $\text{array}, \text{a}, \text{i}, \$1$
10: $+, \text{m}, \text{n}, \$2$
11: $/, \$2, 2, \$3$
12: $\text{array}, \text{a}, \$3, \$4$
13: $<, [\$1], [\$4], 15$
14: $\text{jump}, -, -, 18$
15: $+, \text{i}, 1, \$5$
16: $:=, \$5, -, \text{i}$
17: $\text{jump}, -, -, 9$

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while i <= j do begin
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13: $<, [\$1], [\$4], 15$
14: $\text{jump}, -, -, 18$
15: $+, \text{i}, 1, \$5$
16: $:=, \$5, -, \text{i}$
17: $\text{jump}, -, -, 9$
18: $\text{array}, \text{a}, \text{j}, \$6$

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11: $/, \$2, 2, \$3$
12: $\text{array}, \text{a}, \$3, \$4$
13: $<, [\$1], [\$4], 15$
14: $\text{jump}, -, -, 18$
15: $+, \text{i}, 1, \$5$
16: $:=, \$5, -, \text{i}$
17: $\text{jump}, -, -, 9$
18: $\text{array}, \text{a}, \text{j}, \$6$
19: $+, \text{m}, \text{n}, \$7$

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13: $<, [\$1], [\$4], 15$
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16: $:=, \$5, -, \text{i}$
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19: $+, \text{m}, \text{n}, \$7$
20: $/, \$7, 2, \$8$
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22: $>, [\$6], [\$9], *$

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14: $\text{jump}, -, -, 18$
15: $+, \text{i}, 1, \$5$
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22: $>, [\$6], [\$9], *$
23: $\text{jump}, -, -, *$

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7: $<=$, i, j, 9
8: jump, $-$, $-$, $*$
9: array, a, i, \$1
10: $+$, m, n, \$2
11: $/$, \$2, 2, \$3
12: array, a, \$3, \$4
13: $<$, [\$1], [\$4], 15
14: jump, $-$, $-$, 18
15: $+$, i, 1, \$5
16: $:=$, \$5, $-$, i
17: jump, $-$, $-$, 9
18: array, a, j, \$6
19: $+$, m, n, \$7
20: $/$, \$7, 2, \$8
21: array, a, \$8, \$9
22: $>$, [\$6], [\$9], 24
23: jump, $-$, $-$, $*$

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15: $+, \text{i}, 1, \$5$
16: $:=, \$5, -, \text{i}$
17: $\text{jump}, -, -, 9$
18: $\text{array}, \text{a}, \text{j}, \$6$
19: $+, \text{m}, \text{n}, \$7$
20: $/, \$7, 2, \$8$
21: $\text{array}, \text{a}, \$8, \$9$
22: $>, [\$6], [\$9], 24$
23: $\text{jump}, -, -, *$
24: $-, \text{j}, 1, \$10$

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7: $<=$, i, j, 9
8: jump, $-$, $-$, $*$
9: array, a, i, \$1
10: $+$, m, n, \$2
11: $/$, \$2, 2, \$3
12: array, a, \$3, \$4
13: $<$, [\$1], [\$4], 15
14: jump, $-$, $-$, 18
15: $+$, i, 1, \$5
16: $:=$, \$5, $-$, i
17: jump, $-$, $-$, 9
18: array, a, j, \$6
19: $+$, m, n, \$7
20: $/$, \$7, 2, \$8
21: array, a, \$8, \$9
22: $>$, [\$6], [\$9], 24
23: jump, $-$, $-$, $*$
24: $-$, j, 1, \$10
25: $:=$, \$10, $-$, j

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while i <= j do begin
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16: $:=, \$5, -, \text{i}$
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18: $\text{array}, \text{a}, \text{j}, \$6$
19: $+, \text{m}, \text{n}, \$7$
20: $/, \$7, 2, \$8$
21: $\text{array}, \text{a}, \$8, \$9$
22: $>, [\$6], [\$9], 24$
23: $\text{jump}, -, -, *$
24: $-, \text{j}, 1, \$10$
25: $:=, \$10, -, \text{j}$
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14: $\text{jump}, -, -, 18$
15: $+, \text{i}, 1, \$5$
16: $:=, \$5, -, \text{i}$
17: $\text{jump}, -, -, 9$
18: $\text{array}, \text{a}, \text{j}, \$6$
19: $+, \text{m}, \text{n}, \$7$
20: $/, \$7, 2, \$8$
21: $\text{array}, \text{a}, \$8, \$9$
22: $>, [\$6], [\$9], 24$
23: $\text{jump}, -, -, 27$
24: $-, \text{j}, 1, \$10$
25: $:=, \$10, -, \text{j}$
26: $\text{jump}, -, -, 18$

Example (iv)

```
if i <= j then begin
  temp := a[i]; a[i] := a[j]; a[j] := temp;
  i := i+1; j := j-1
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```

27: $<=, \mathrm{i}, \mathrm{j}, *$
28: $\mathrm{jump}, -, -, *$

Example (iv)

```
if i <= j then begin
  temp := a[i]; a[i] := a[j]; a[j] := temp;
  i := i+1; j := j-1
end
```

27: $<=$, i, j, 29
28: jump, $-$, $-$, $*$

Example (iv)

```
if i <= j then begin
  temp := a[i]; a[i] := a[j]; a[j] := temp;
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end
```

27: $<=, \text{i}, \text{j}, 29$
28: $\text{jump}, -, -, *$
29: $\text{array}, \text{a}, \text{i}, \$11$

Example (iv)

```
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27: $<=, \text{i}, \text{j}, 29$
28: $\text{jump}, -, -, *$
29: $\text{array}, \text{a}, \text{i}, \$11$
30: $:=, [\$11], -, \text{temp}$

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```

27: $<=$, i, j, 29
28: jump, $-$, $-$, $*$
29: array, a, i, \$11
30: $:=$, [\$11], $-$, temp
31: array, a, i, \$12

Example (iv)

```
if i <= j then begin
  temp := a[i]; a[i] := a[j]; a[j] := temp;
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```

27: $<=$, i, j, 29
28: jump, $-$, $-$, $*$
29: array, a, i, \$11
30: $:=$, [\$11], $-$, temp
31: array, a, i, \$12
32: array, a, j, \$13

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27: $<=$, i, j, 29
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29: array, a, i, \$11
30: $:=$, [\$11], $-$, temp
31: array, a, i, \$12
32: array, a, j, \$13
33: $:=$, [\$13], $-$, [\$12]

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27: $<=$, i, j, 29
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29: array, a, i, \$11
30: $:=$, [\$11], $-$, temp
31: array, a, i, \$12
32: array, a, j, \$13
33: $:=$, [\$13], $-$, [\$12]

34: array, a, j, \$14

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30: $:=$, [\$11], $-$, temp
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32: array, a, j, \$13
33: $:=$, [\$13], $-$, [\$12]
34: array, a, j, \$14
35: $:=$, temp, $-$, [\$14]

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31: array, a, i, \$12
32: array, a, j, \$13
33: $:=$, [\$13], $-$, [\$12]
34: array, a, j, \$14
35: $:=$, temp, $-$, [\$14]
36: $+$, i, 1, \$15

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34: array, a, j, \$14
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36: $+$, i, 1, \$15
37: $:=$, \$15, $-$, i
38: $-$, j, 1, \$16

Example (iv)

```
if i <= j then begin
  temp := a[i]; a[i] := a[j]; a[j] := temp;
  i := i+1; j := j-1
end
```

27: $<=$, i, j, 29
28: jump, $-$, $-$, $*$
29: array, a, i, \$11
30: $:=$, [\$11], $-$, temp
31: array, a, i, \$12
32: array, a, j, \$13
33: $:=$, [\$13], $-$, [\$12]
34: array, a, j, \$14
35: $:=$, temp, $-$, [\$14]
36: $+$, i, 1, \$15
37: $:=$, \$15, $-$, i
38: $-$, j, 1, \$16
39: $:=$, \$16, $-$, j

Example (v)

```
while i <= j do begin
  while a[i] < a[(m+n) div 2] do i := i+1;
  while a[j] > a[(m+n) div 2] do j := j-1;
  if i <= j then begin
    temp := a[i]; a[i] := a[j]; a[j] := temp;
    i := i+1; j := j-1
  end
end;
```

Example (v)

```
while i <= j do begin
  while a[i] < a[(m+n) div 2] do i := i+1;
  while a[j] > a[(m+n) div 2] do j := j-1;
  if i <= j then begin
    temp := a[i]; a[i] := a[j]; a[j] := temp;
    i := i+1; j := j-1
  end
end;
```

7: $<=, \mathrm{i}, \mathrm{j}, 9$

8: $\mathrm{jump}, -, -, *$

Example (v)

```
while i <= j do begin
  while a[i] < a[(m+n) div 2] do i := i+1;
  while a[j] > a[(m+n) div 2] do j := j-1;
  if i <= j then begin
    temp := a[i]; a[i] := a[j]; a[j] := temp;
    i := i+1; j := j-1
  end
end;
```

7: $<=, \mathrm{i}, \mathrm{j}, 9$

8: $\mathrm{jump}, -, -, *$

...

27: $<=, \mathrm{i}, \mathrm{j}, 29$

28: $\mathrm{jump}, -, -, *$

Example (v)

```
while i <= j do begin
  while a[i] < a[(m+n) div 2] do i := i+1;
  while a[j] > a[(m+n) div 2] do j := j-1;
  if i <= j then begin
    temp := a[i]; a[i] := a[j]; a[j] := temp;
    i := i+1; j := j-1
  end
end;
```

7: $<=, \mathrm{i}, \mathrm{j}, 9$

8: $\mathrm{jump}, -, -, *$

...

27: $<=, \mathrm{i}, \mathrm{j}, 29$

28: $\mathrm{jump}, -, -, *$

...

40: $\mathrm{jump}, -, -, 7$

Example (v)

```
while i <= j do begin
  while a[i] < a[(m+n) div 2] do i := i+1;
  while a[j] > a[(m+n) div 2] do j := j-1;
  if i <= j then begin
    temp := a[i]; a[i] := a[j]; a[j] := temp;
    i := i+1; j := j-1
  end
end;
```

7: $<=, \mathrm{i}, \mathrm{j}, 9$
8: $\mathrm{jump}, -, -, *$
...
27: $<=, \mathrm{i}, \mathrm{j}, 29$
28: $\mathrm{jump}, -, -, 7$
...
40: $\mathrm{jump}, -, -, 7$

Example (v)

```
while i <= j do begin
  while a[i] < a[(m+n) div 2] do i := i+1;
  while a[j] > a[(m+n) div 2] do j := j-1;
  if i <= j then begin
    temp := a[i]; a[i] := a[j]; a[j] := temp;
    i := i+1; j := j-1
  end
end;
```

7: $<=, \mathrm{i}, \mathrm{j}, 9$
8: $\mathrm{jump}, -, -, 41$
...
27: $<=, \mathrm{i}, \mathrm{j}, 29$
28: $\mathrm{jump}, -, -, 7$
...
40: $\mathrm{jump}, -, -, 7$

Example (vi)

```
  quicksort(a, m, j); quicksort(a, i, n)
end;
```

Example (vi)

```
  quicksort(a, m, j); quicksort(a, i, n)
end;
```

41: par, a, R, —

Example (vi)

```
  quicksort(a, m, j); quicksort(a, i, n)
end;
```

41: par, a, R, –
42: par, m, V, –

Example (vi)

```
  quicksort(a, m, j); quicksort(a, i, n)
end;
```

41: par, a, R, –
42: par, m, V, –
43: par, j, V, –

Example (vi)

```
  quicksort(a, m, j); quicksort(a, i, n)
end;
```

41: par, a, R, —
42: par, m, V, —
43: par, j, V, —
44: call, —, —, quicksort

Example (vi)

```
  quicksort(a, m, j); quicksort(a, i, n)
end;
```

41: par, a, R, —
42: par, m, V, —
43: par, j, V, —
44: call, —, —, quicksort
45: par, a, R, —

Example (vi)

```
  quicksort(a, m, j); quicksort(a, i, n)
end;
```

41: par, a, R, —
42: par, m, V, —
43: par, j, V, —
44: call, —, —, quicksort
45: par, a, R, —
46: par, i, V, —

Example (vi)

```
  quicksort(a, m, j); quicksort(a, i, n)
end;
```

41: par, a, R, –
42: par, m, V, –
43: par, j, V, –
44: call, –, –, quicksort
45: par, a, R, –
46: par, i, V, –
47: par, n, V, –

Example (vi)

```
  quicksort(a, m, j); quicksort(a, i, n)
end;
```

41: par, a, R, —
42: par, m, V, —
43: par, j, V, —
44: call, —, —, quicksort
45: par, a, R, —
46: par, i, V, —
47: par, n, V, —
48: call, —, —, quicksort

Example (vi)

```
  quicksort(a, m, j); quicksort(a, i, n)
end;
```

41: par, a, R, –
42: par, m, V, –
43: par, j, V, –
44: call, –, –, quicksort
45: par, a, R, –
46: par, i, V, –
47: par, n, V, –
48: call, –, –, quicksort
49: endu, quicksort, –, –