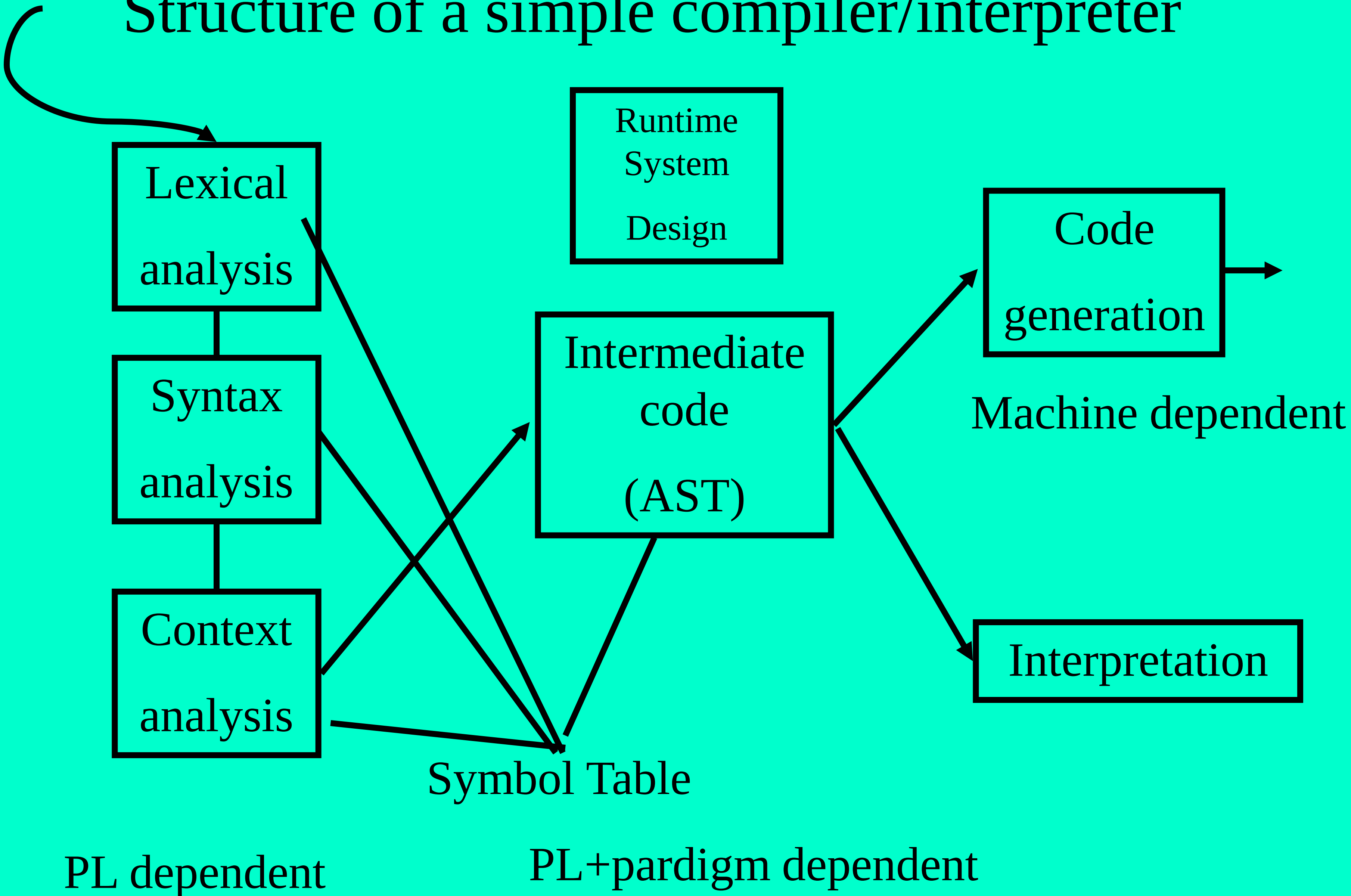
Introduction to Code Generation

Mooly Sagiv

html://www.cs.tau.ac.il/~msagiv/courses/wcc10.html

Chapter 4

Structure of a simple compiler/interpreter



Outline

- Interpreters
- Code Generation

Types of Interpreters

- Recursive
  - Recursively traverse the tree
  - Uniform data representation
  - Conceptually clean
  - Excellent error detection
  - 1000x slower than compiler
- Iterative
  - Closer to CPU
  - One flat loop
  - Explicit stack
  - Good error detection
  - 30x slower than compiler
  - Can invoke compiler on code fragments

Input language (Overview)

- Fully parameterized expressions
- Arguments can be a single digit

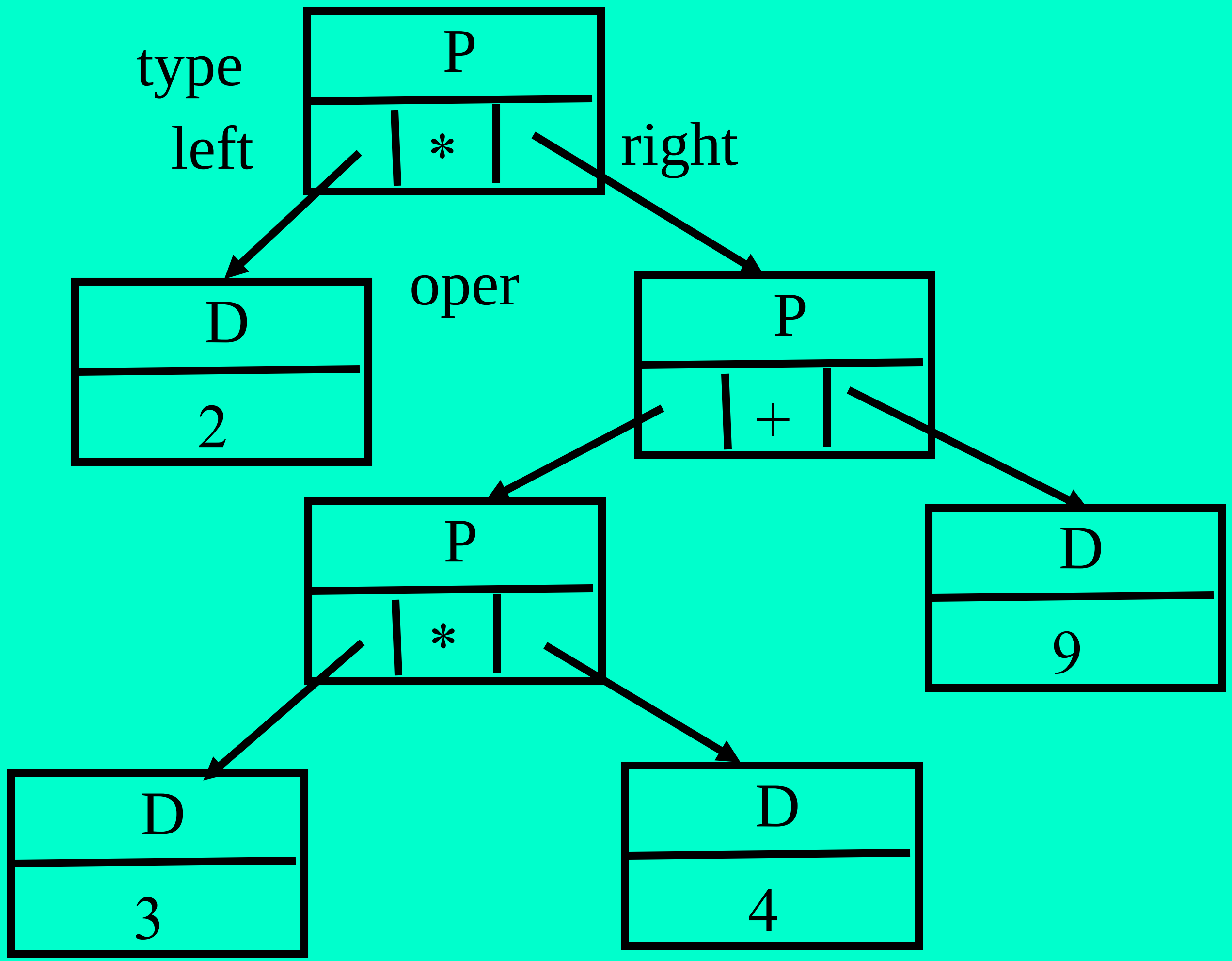
expression → digit | ‘(‘ expression operator expression ‘)’

operator → ‘+’ | ‘*’

digit → ‘0’ | ‘1’ | ‘2’ | ‘3’ | ‘4’ | ‘5’ | ‘6’ | ‘7’ | ‘8’ | ‘9’

```
#include    "parser.h"
#include "backend.h"
static int Interpret_expression(Expression *expr) {
    switch (expr->type) {
    case 'D':
        return expr->value;
        break;
    case 'P': {
        int e_left = Interpret_expression(expr->left);
        int e_right = Interpret_expression(expr->right);
        switch (expr->oper) {
        case '+': return e_left + e_right;
        case '*': return e_left * e_right;
        }}
        break;
    }
}
void Process(AST_node *icode) {
    printf("%d\n", Interpret_expression(icode));
}
```

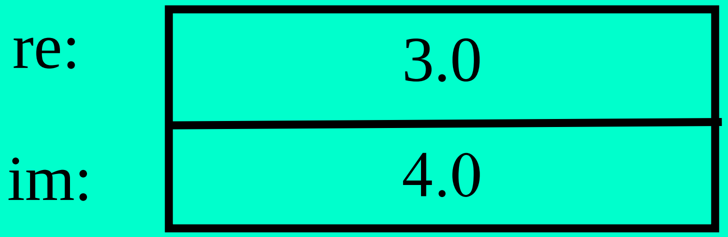
AST for (2 * ((3*4)+9))

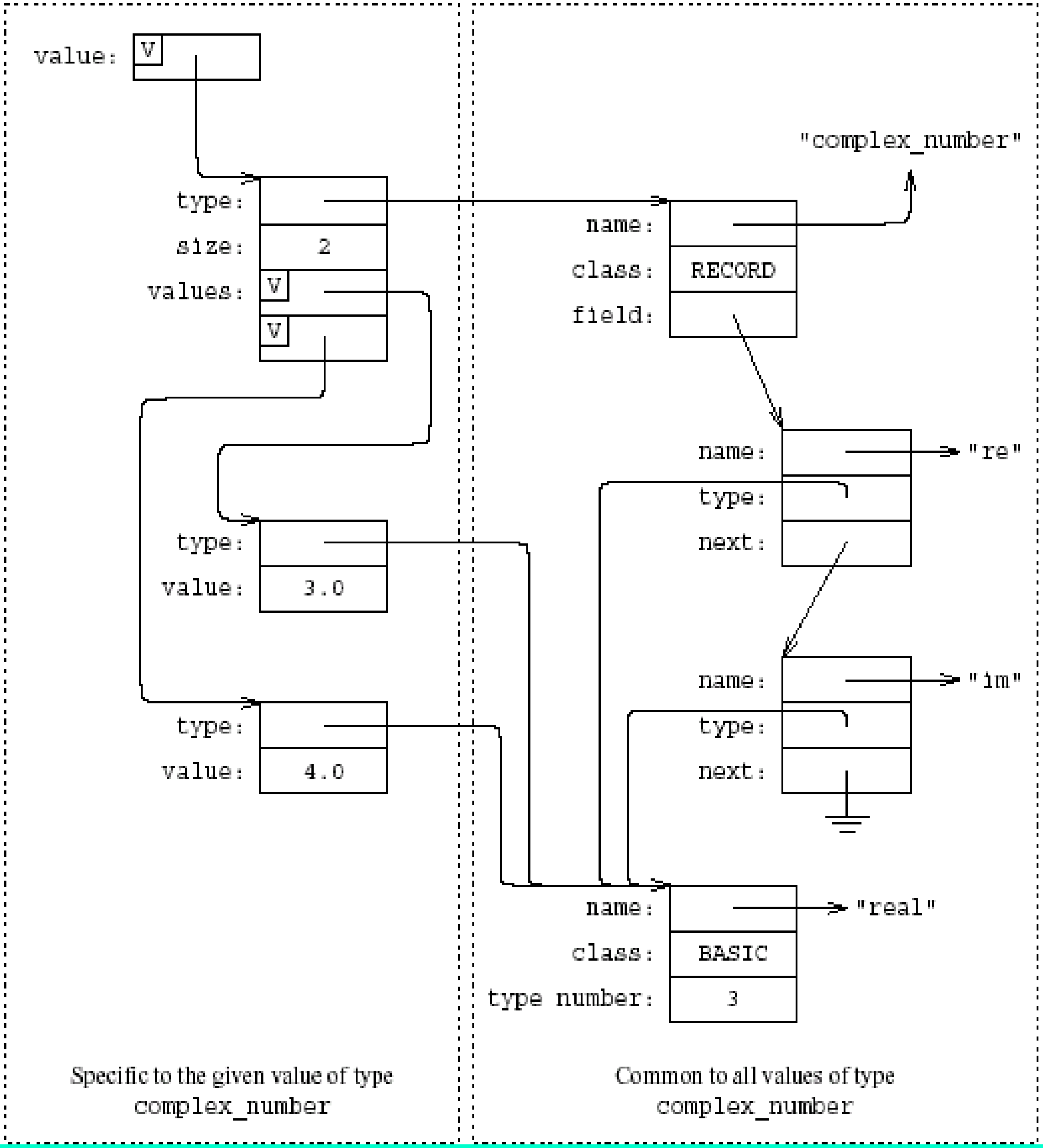


Uniform self-identifying data representation

- The types of the sizes of program data values are not known when the interpreter is written
- Uniform representation of data types
  - Type
  - Size
- The value is a pointer

Example: Complex Number

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value:
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class:
RECORD
field:
name:
"re"
type:
next:
name:
"im"
type:
next:
name:
"real"
class:
BASIC
type number:
3
Common to all values of type complex_number

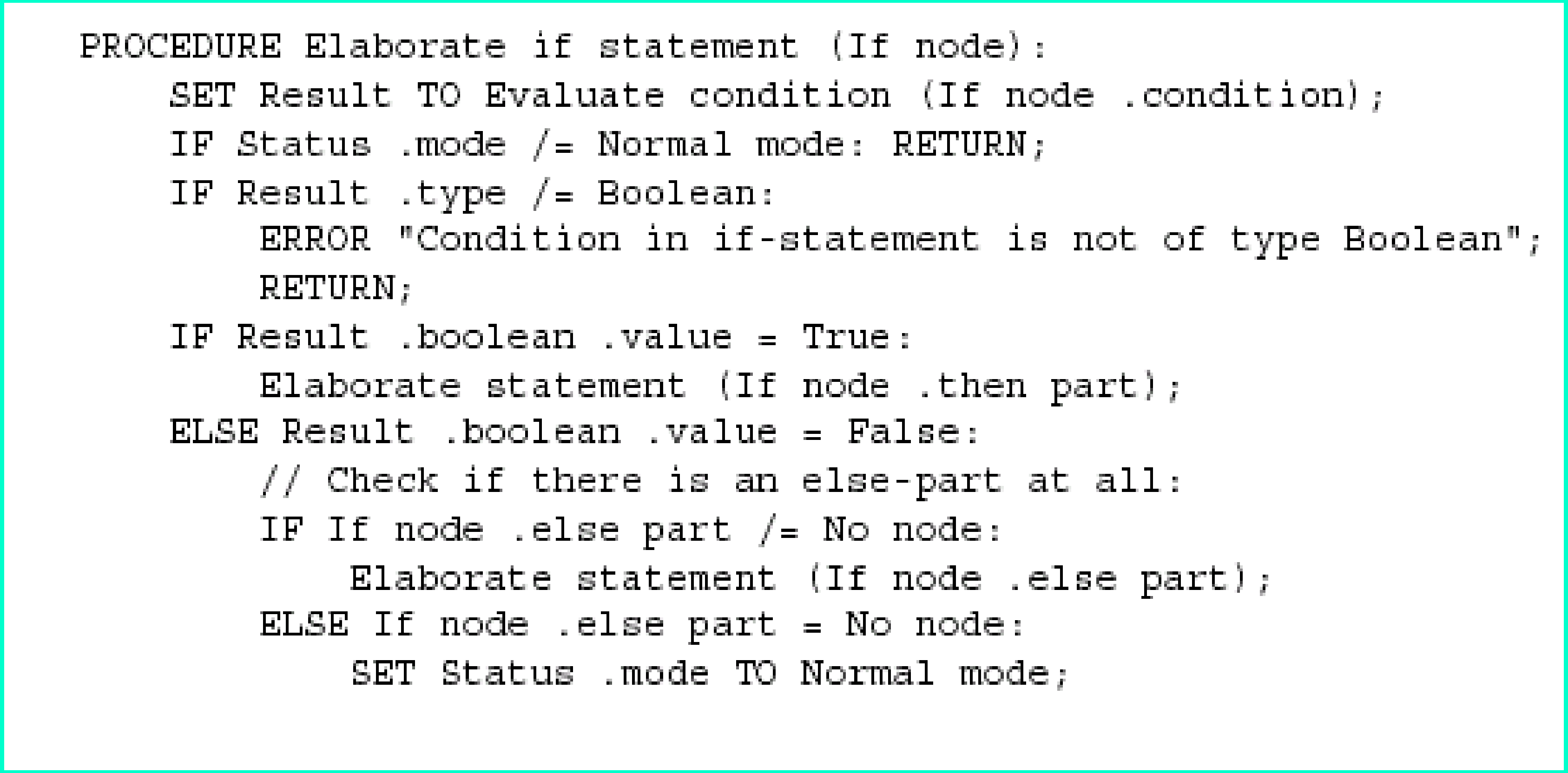
Status Indicator

- Direct control flow of the interpreter
- Possible values
  - Normal mode
  - Errors
  - Jumps
  - Exceptions
  - Return

Example: Interpreting C Return

```
PROCEDURE Elaborate return with expression statement (RWE node):
    SET Result To Evaluate expression (RWE node . expression);
    IF Status . mode /= Normal mode: Return mode;
    SET Status . mode To Return mode;
    SET Status . value TO Result;
```

Interpreting If-Statement



```
PROCEDURE Elaborate if statement (If node):
    SET Result TO Evaluate condition (If node .condition);
    IF Status .mode /= Normal mode: RETURN;
    IF Result .type /= Boolean:
        ERROR "Condition in if-statement is not of type Boolean";
        RETURN;
    IF Result .boolean .value = True:
        Elaborate statement (If node .then part);
    ELSE Result .boolean .value = False:
        // Check if there is an else-part at all:
        IF If node .else part /= No node:
            Elaborate statement (If node .else part);
        ELSE If node .else part = No node:
            SET Status .mode TO Normal mode;
```

Symbol table

- Stores content of variables, named constants, …
- For every variable V of type T
  - A pointer to the name of V
  - The file name and the line it is declared
  - Kind of declaration
  - A pointer to T
  - A pointer to newly allocated space
  - Initialization bit
  - Language dependent information (e.g. scope)

Summary Recursive Interpreters

- Can be implemented quickly
  - Debug the programming language
- Not good for heavy-duty interpreter
  - Slow
  - Can employ general techniques to speed the recursive interpreter
    - Memoization
    - Tail call elimination
    - Partial evaluation

Memoization

```
int fib(int n)
{
  if (n == 0) return 0 ;
  if (n==1) return 1;
  return fib(n-1) + fib(n-2) ;
 }
```

⇒

```
int sfib[100] = {-1, -1, …, -1}
int fib(int n)
{
  if (sfib[n] > 0) return sfib[n];
  if (n == 0) return 0 ;
  if (n==1) return 1;
  sfib[n] = fib(n-1) + fib(n-2) ;
  return sfib[n];
 }
```

Tail Call Elimination

```
void a(…)
{
  …
  b();
 }
void b(){
code;
}
```

$\Rightarrow$

```
void a(…)
{
  …
  code;
 }
void b(){
code;
}
```

Tail Call Elimination

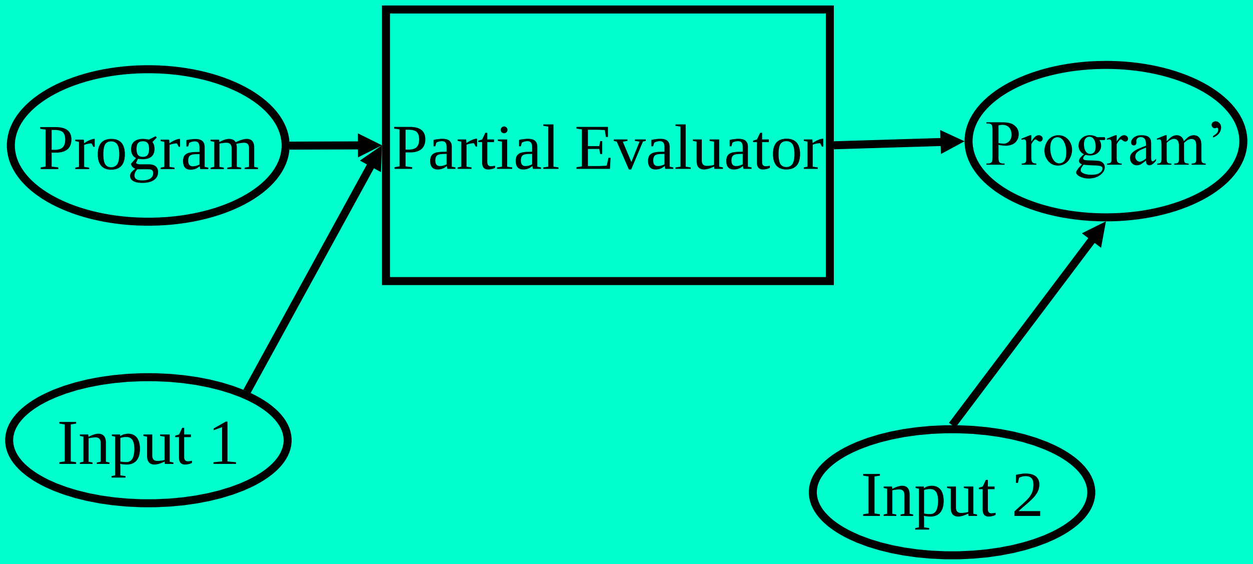
```
void a(int n)
{
  code
  if (n > 0) a(n-1);
 }
```

⇒

```
void a(int n)
{
  loop:
    code
    if (n > 0) {
       n = n -1 ;
       goto loop
 }
```

Partial Evaluation

- Partially interpret static parts in a program
- Generates an equivalent program



Example

```
int pow(int n, int e)
 {
   if (e==0)
        return 1;
   else return n * pow(n, e-1);
 }
```

```
int pow4(int n)
 {
   return n * n * n *n;
 }
```

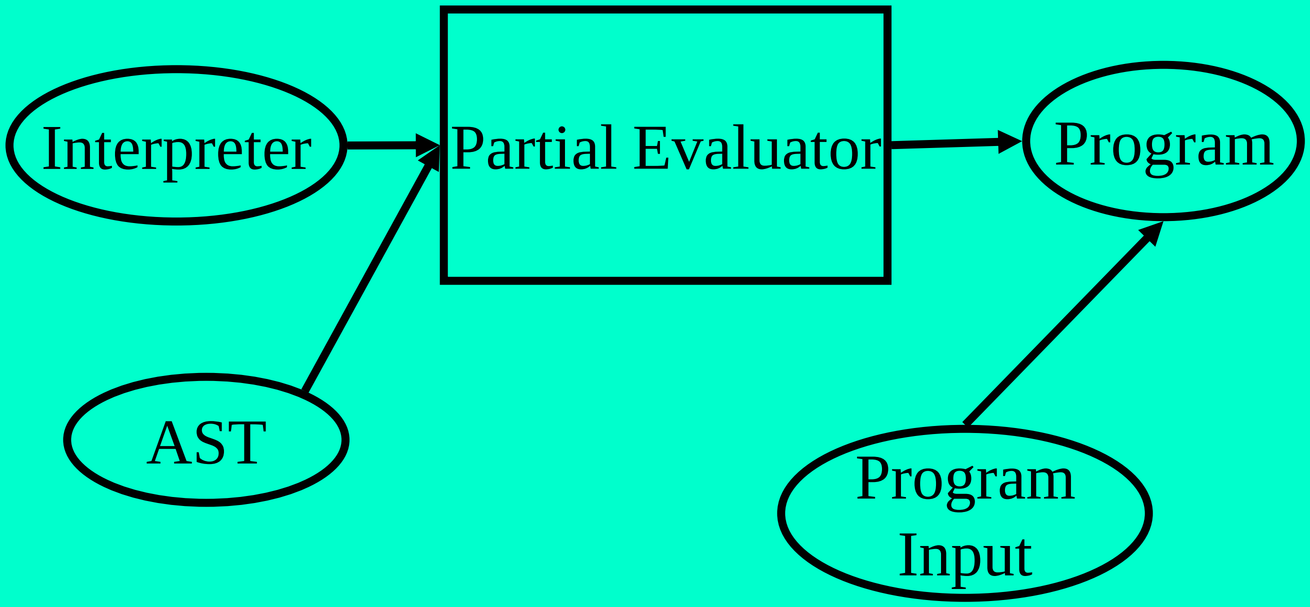
e=4

Example2

```
Bool match(string, regexp)
 {
  switch(regexp) {
        ….
   }
 }
```

regexp=a b*

Partial Evaluation Generalizes Compilation

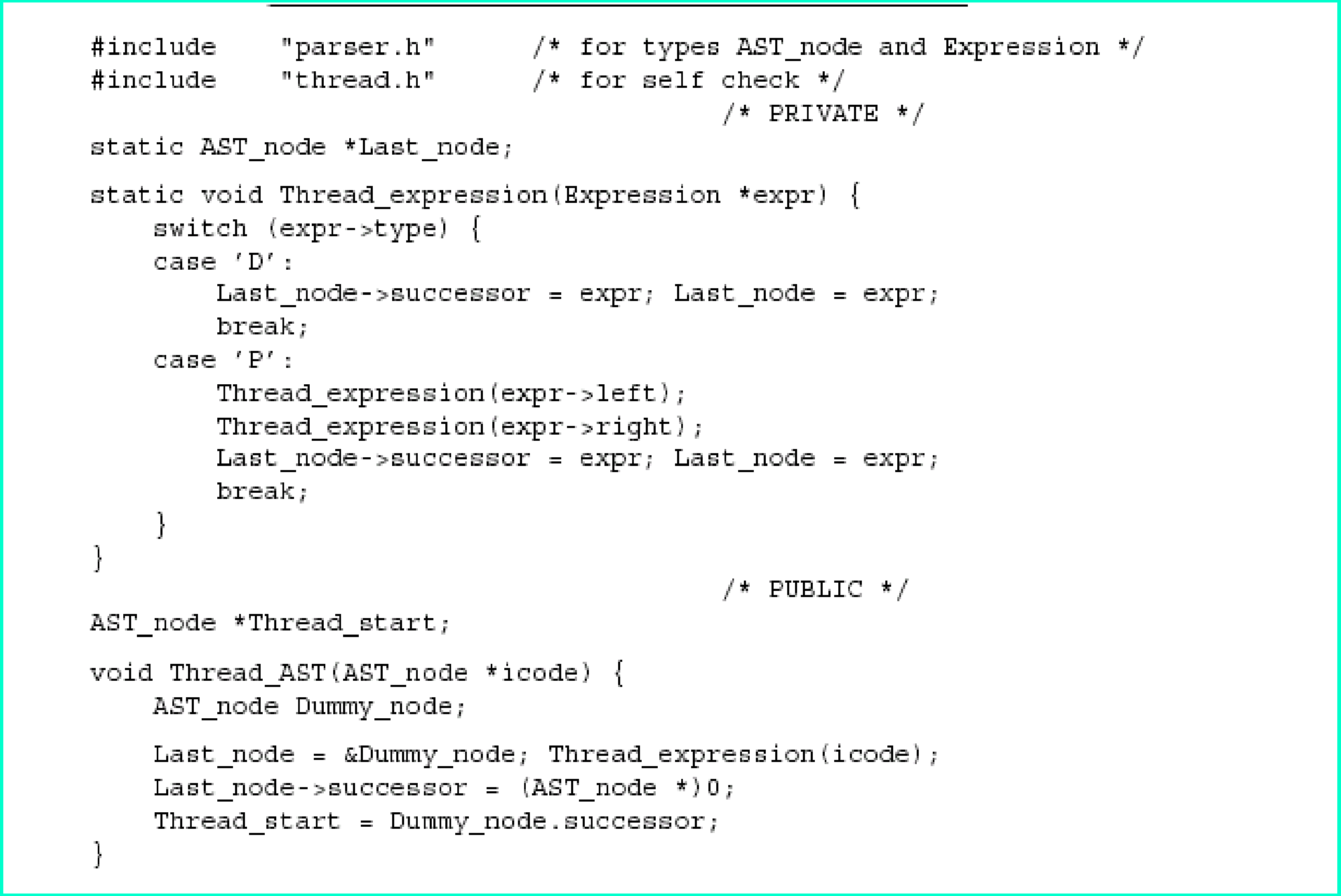


But ….

Iterative Interpretation

- Closed to CPU
- One flat loop with one big case statement
- Use explicit stack
  - Intermediate results
  - Local variables
- Requires fully annotated threaded AST
  - Active-node-pointer (interpreted node)

Demo Compiler



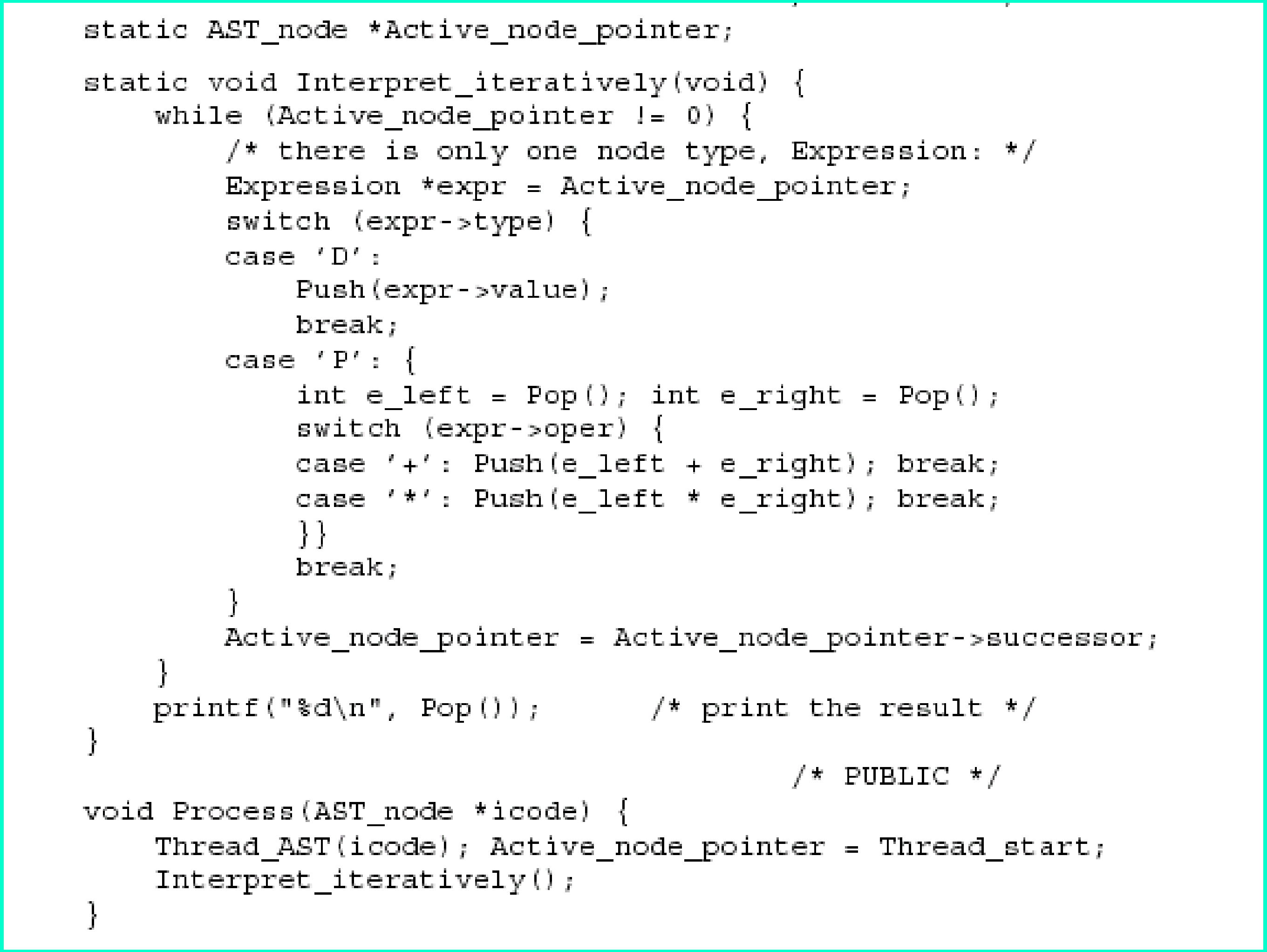
```
#include    "parser.h"      /* for types AST_node and Expression */
#include    "thread.h"      /* for self check */
                                        /* PRIVATE */
static AST_node *Last_node;

static void Thread_expression(Expression *expr) {
    switch (expr->type) {
    case 'D':
        Last_node->successor = expr; Last_node = expr;
        break;
    case 'P':
        Thread_expression(expr->left);
        Thread_expression(expr->right);
        Last_node->successor = expr; Last_node = expr;
        break;
    }
}
                                        /* PUBLIC */
AST_node *Thread_start;

void Thread_AST(AST_node *icode) {
    AST_node Dummy_node;

    Last_node = &Dummy_node; Thread_expression(icode);
    Last_node->successor = (AST_node *)0;
    Thread_start = Dummy_node.successor;
}
```

Demo Compiler



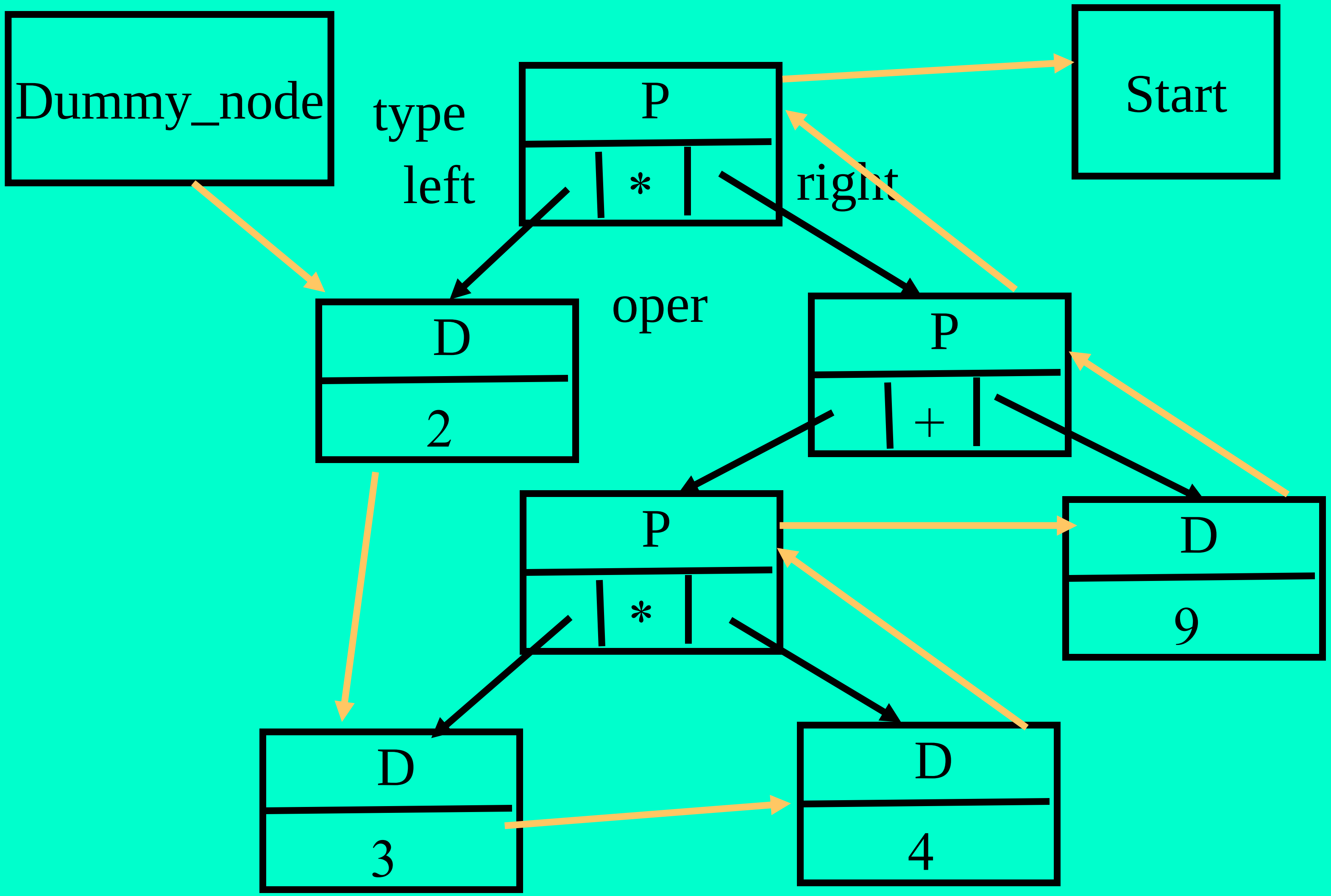
```
static AST_node *Active_node_pointer;

static void Interpret_iteratively(void) {
    while (Active_node_pointer != 0) {
        /* there is only one node type, Expression: */
        Expression *expr = Active_node_pointer;
        switch (expr->type) {
        case 'D':
            Push(expr->value);
            break;
        case 'P': {
            int e_left = Pop(); int e_right = Pop();
            switch (expr->oper) {
            case '+': Push(e_left + e_right); break;
            case '*': Push(e_left * e_right); break;
            }}
            break;
        }
        Active_node_pointer = Active_node_pointer->successor;
    }
    printf("%d\n", Pop());      /* print the result */
}
                                        /* PUBLIC */
void Process(AST_node *icode) {
    Thread_AST(icode); Active_node_pointer = Thread_start;
    Interpret_iteratively();
}
```

Threaded AST

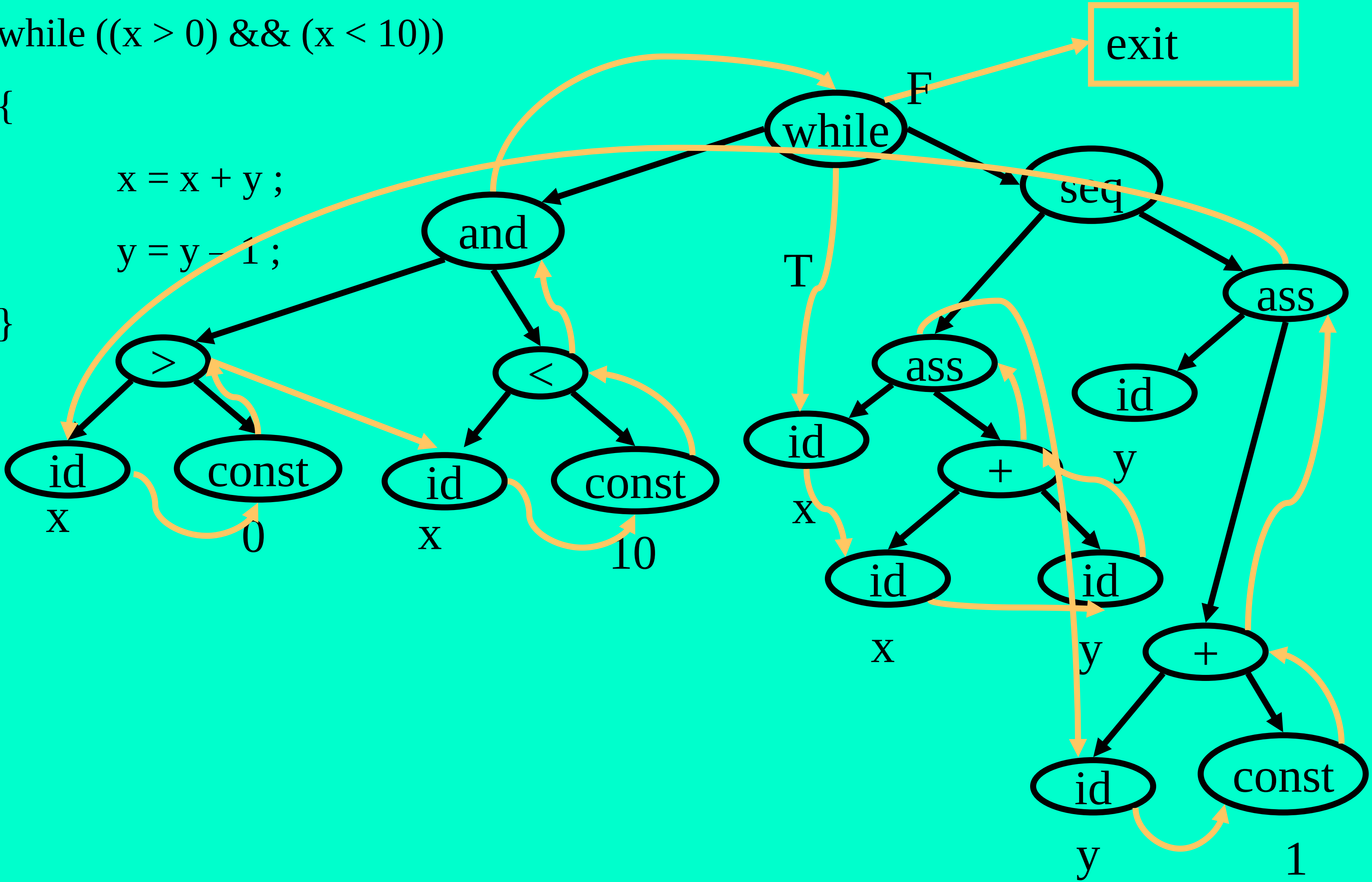
- Annotated AST
- Every node is connected to the immediate successor in the execution
- Control flow graph
  - Nodes
    - Basic execution units
      - expressions
      - assignments
  - Edges
    - Transfer of control
      - sequential
      - while
      - …

Threaded AST for (2 * ((3*4)+9))



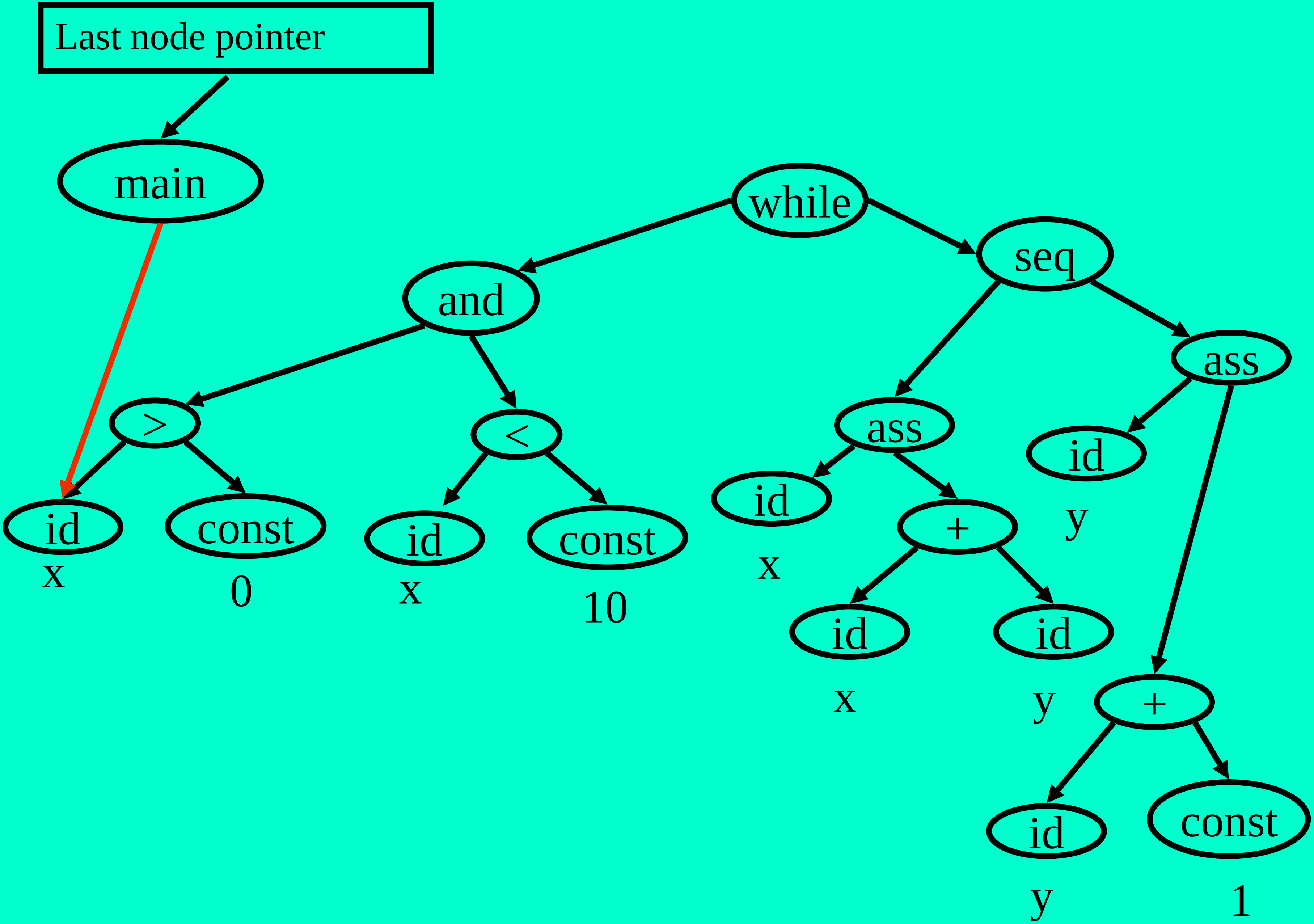
C Example

```
while ((x > 0) && (x < 10))
{
        x = x + y ;
        y = y – 1 ;
}
```



Threading the AST(3.2.1)

- One preorder AST pass
- Every type of AST has its threading routine
- Maintains Last node pointer
  - Global variable
- Set successor of Last pointer when node is visited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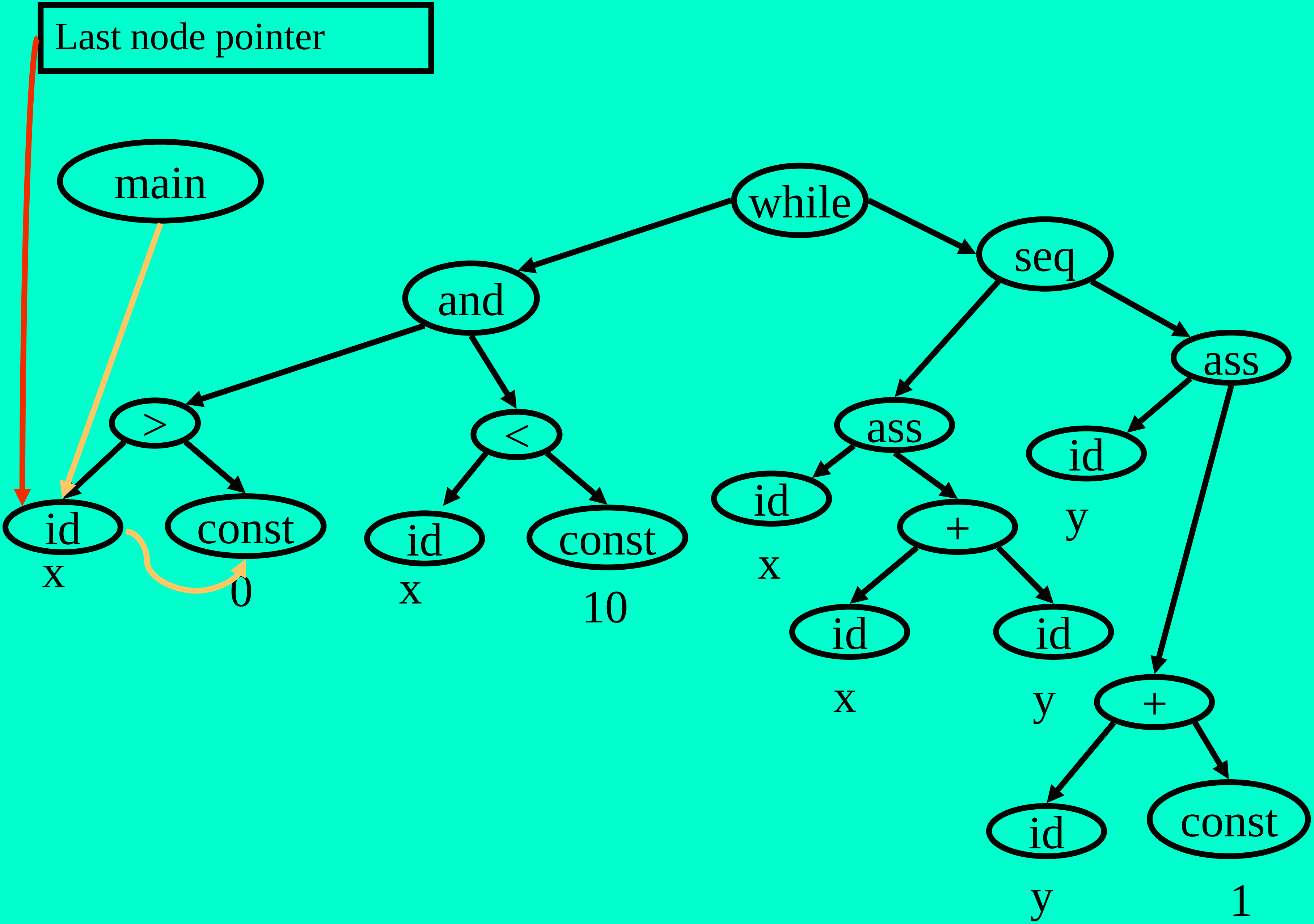
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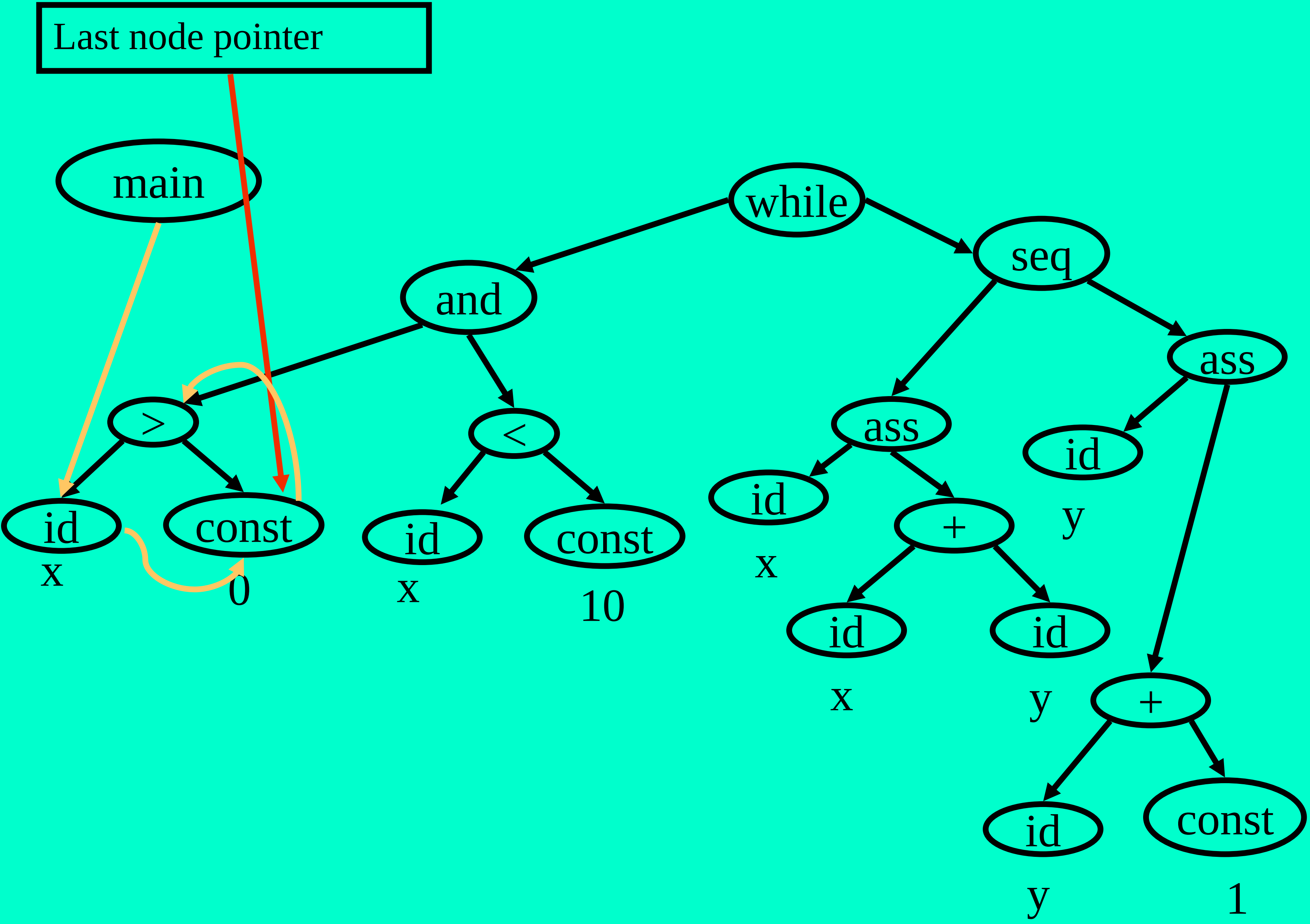
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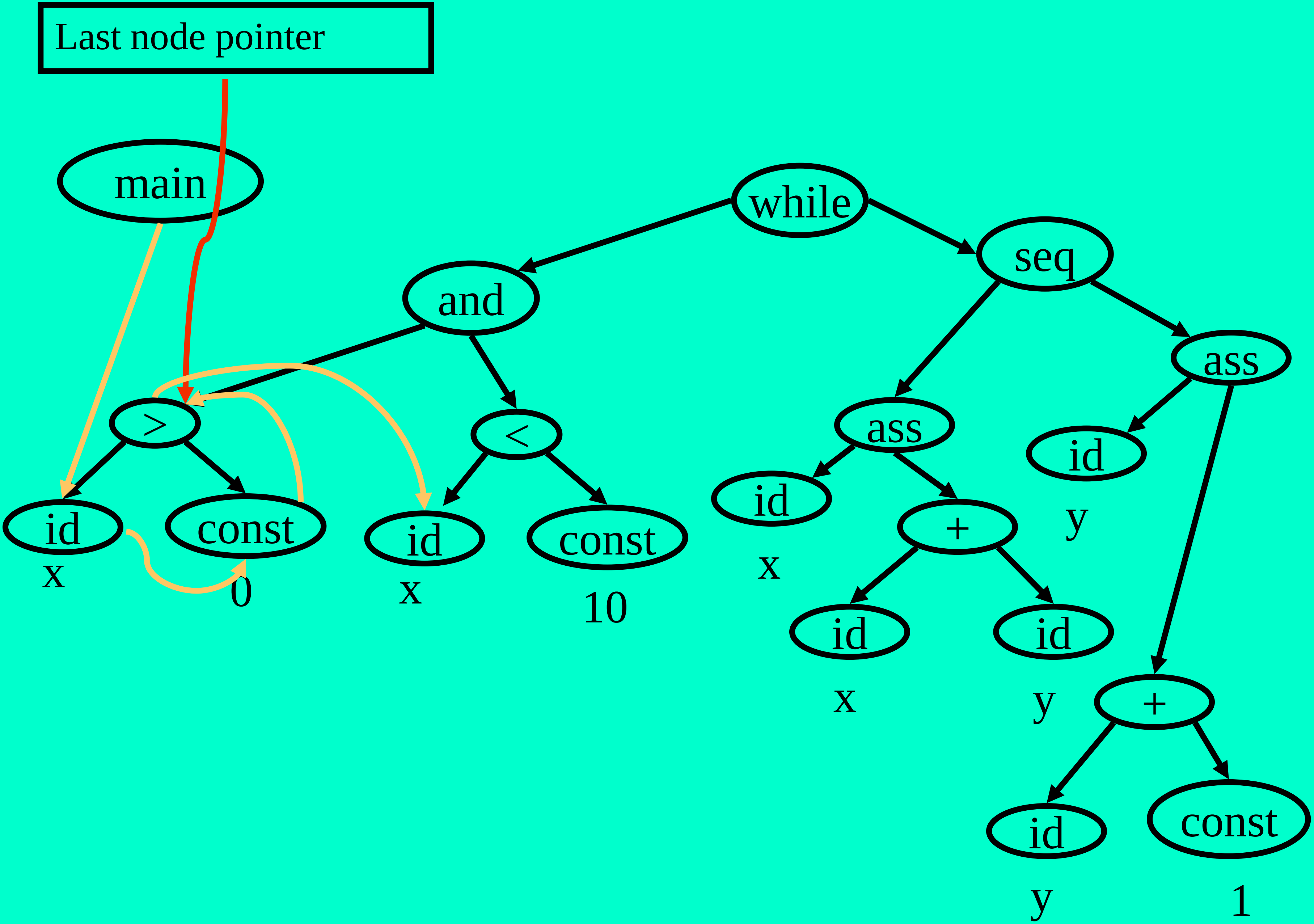
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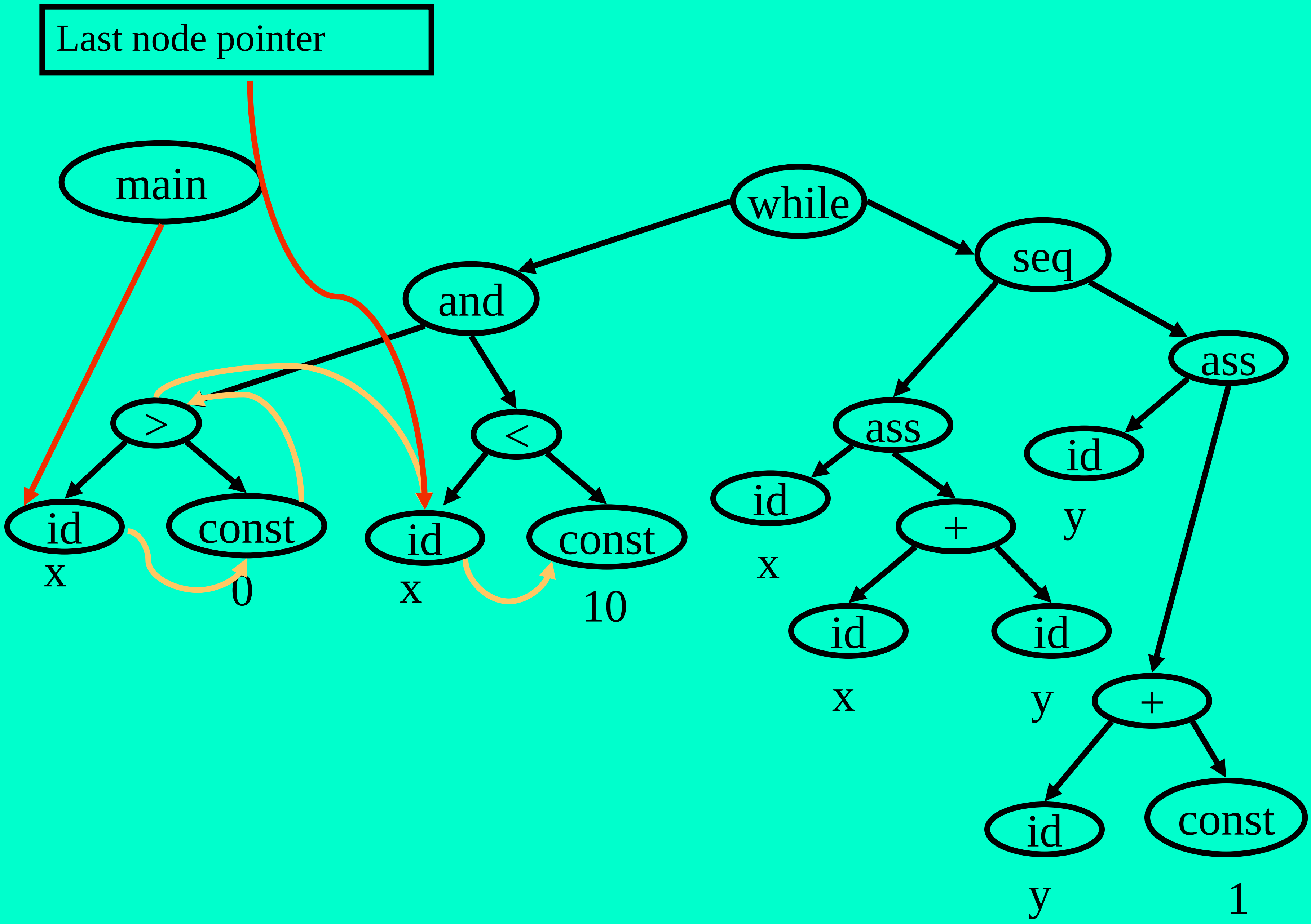
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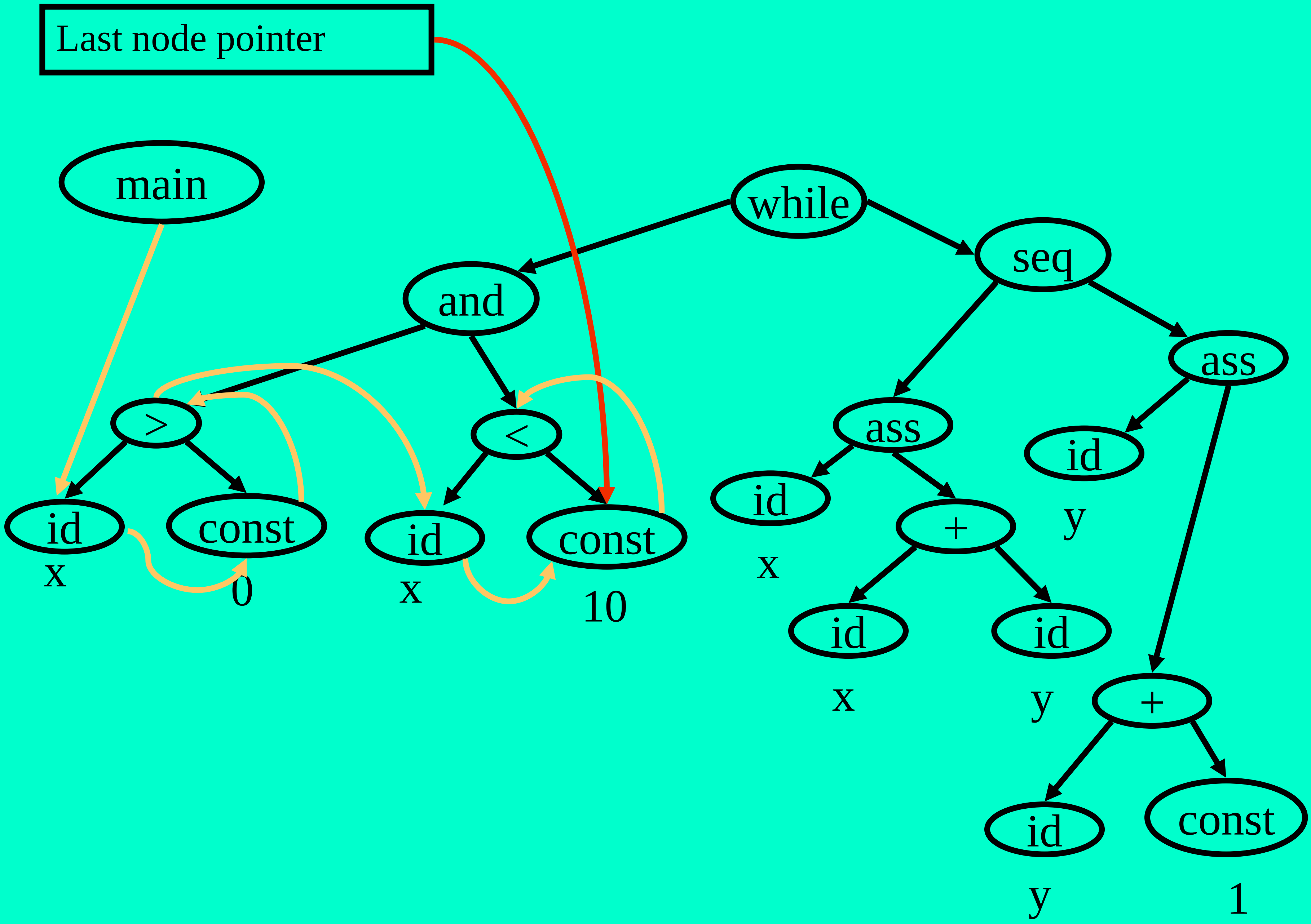
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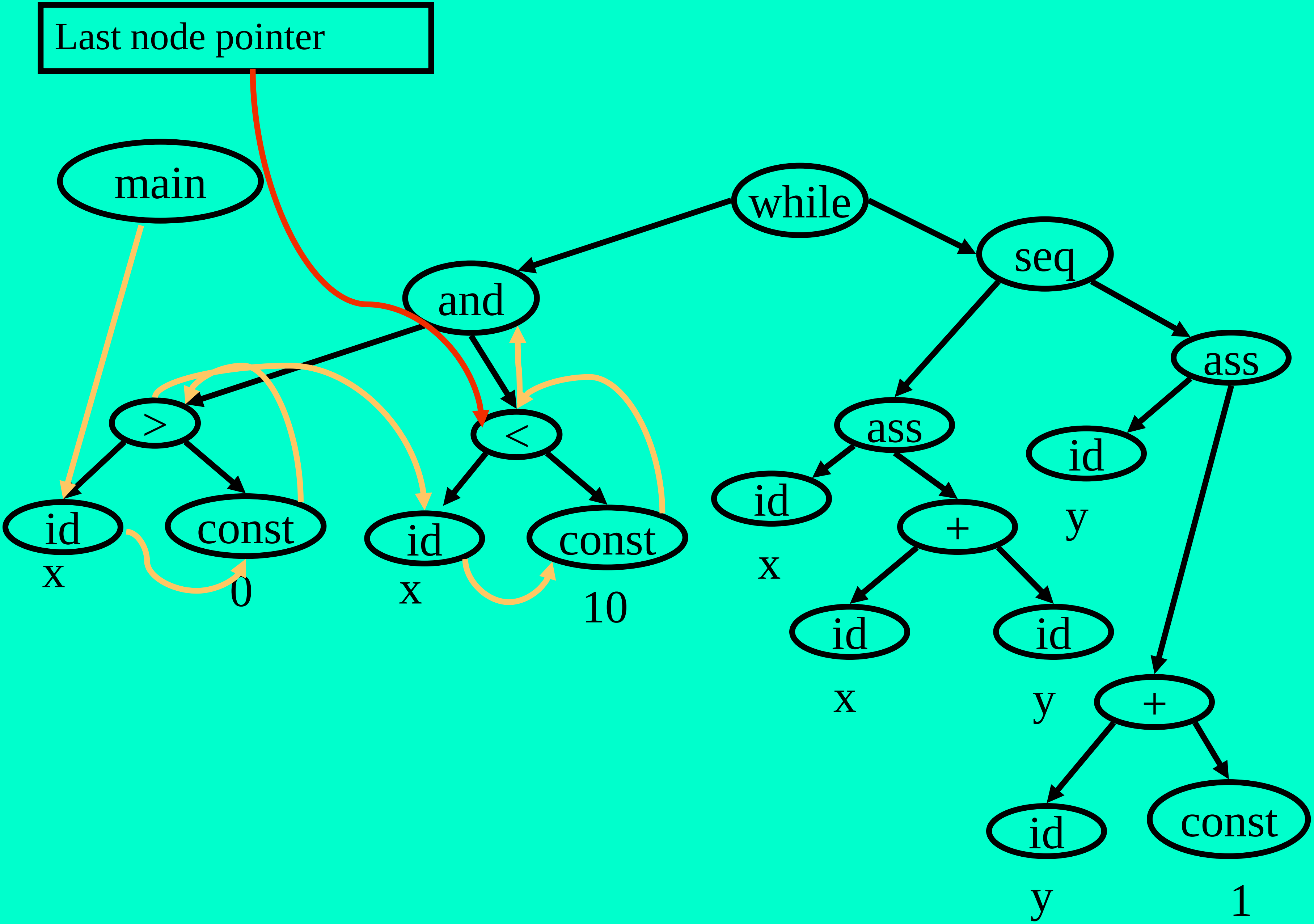
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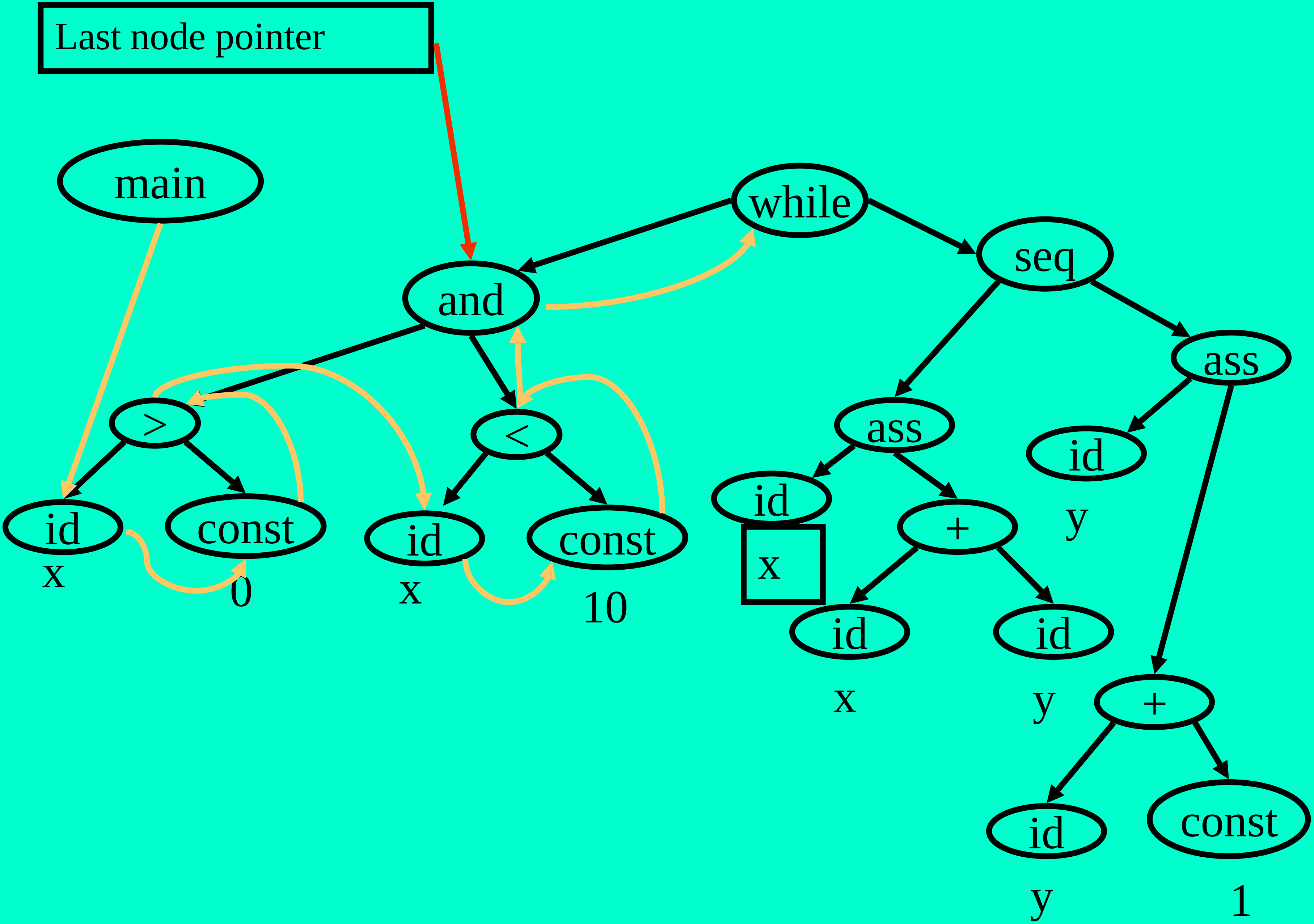
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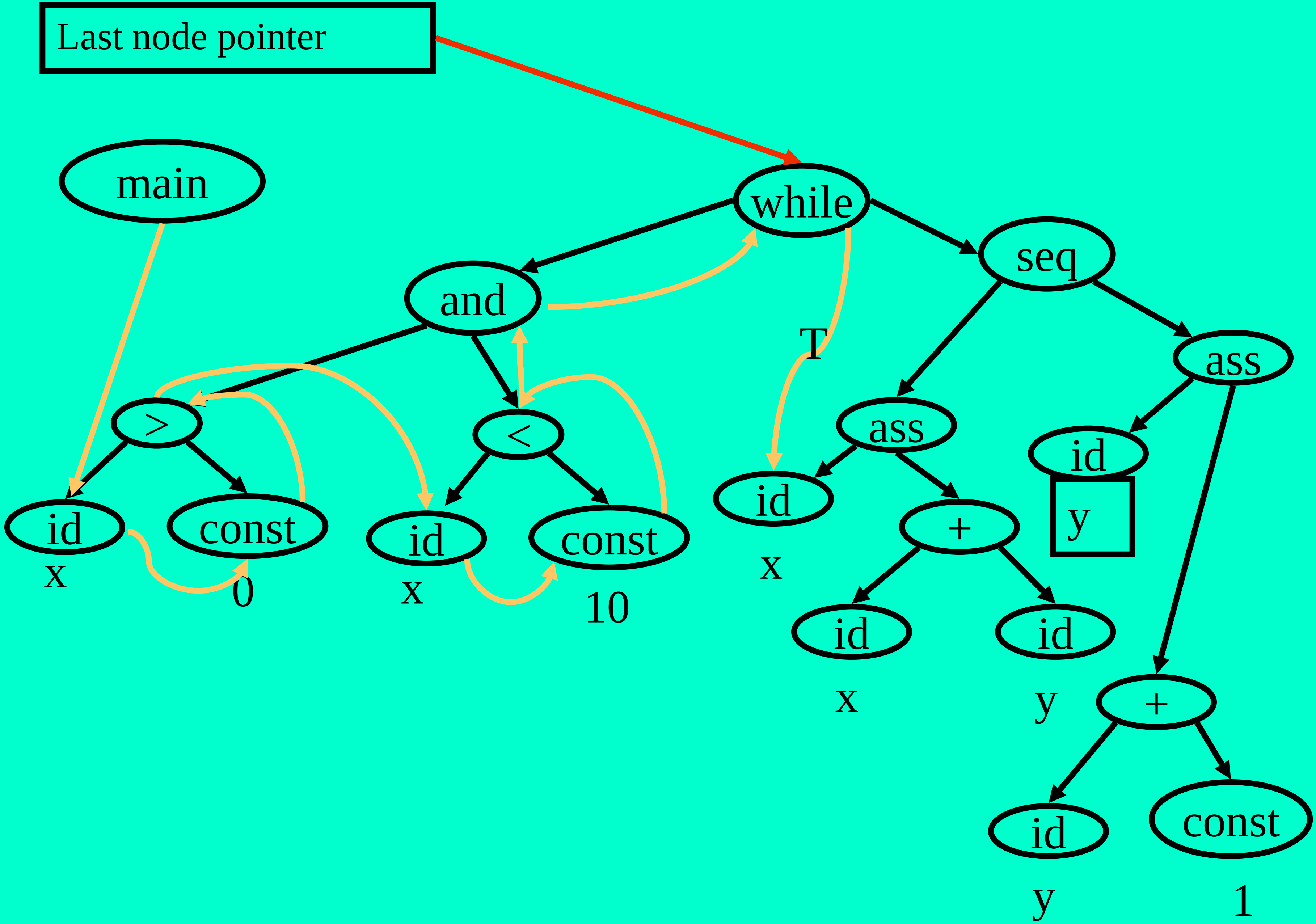
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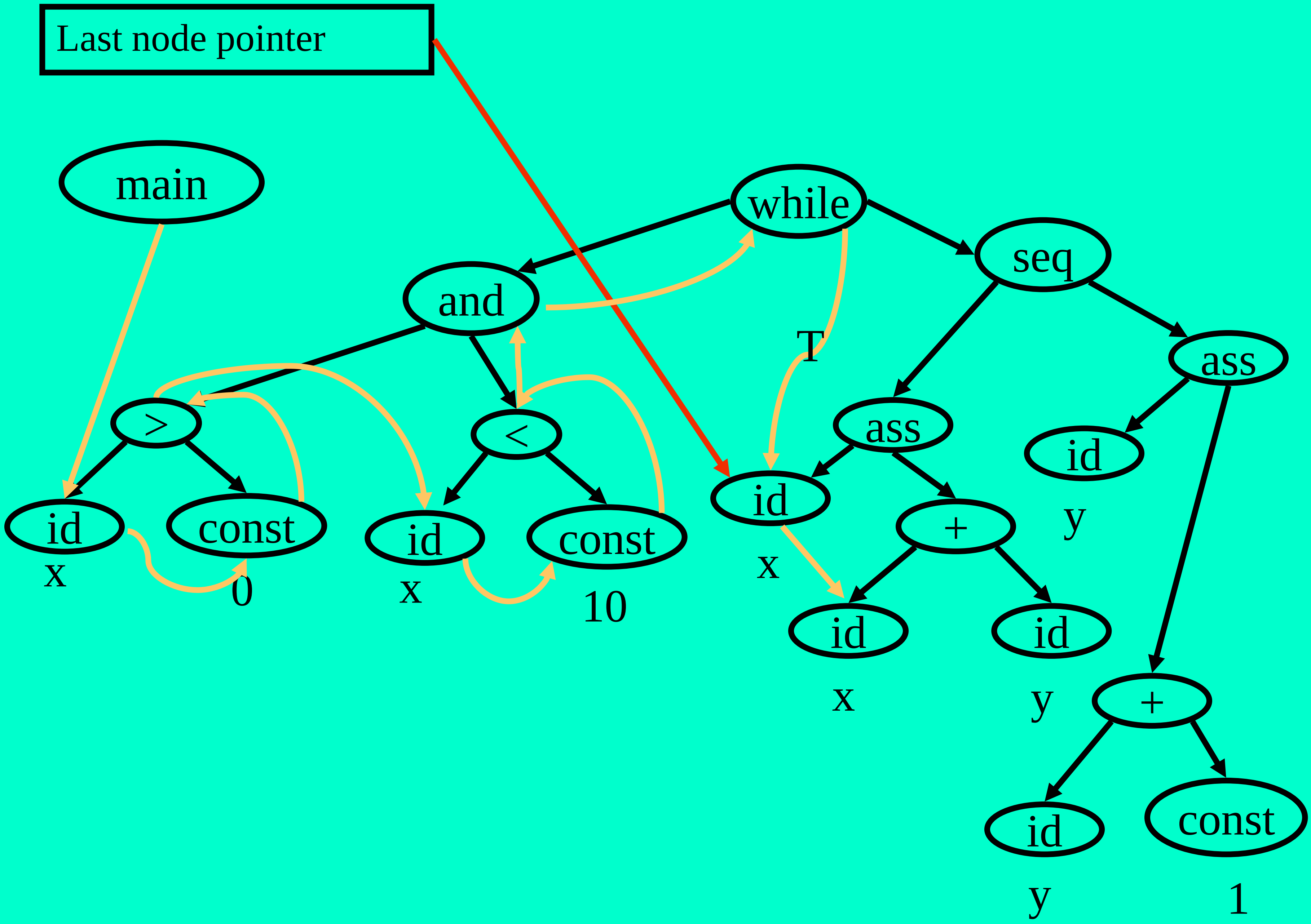
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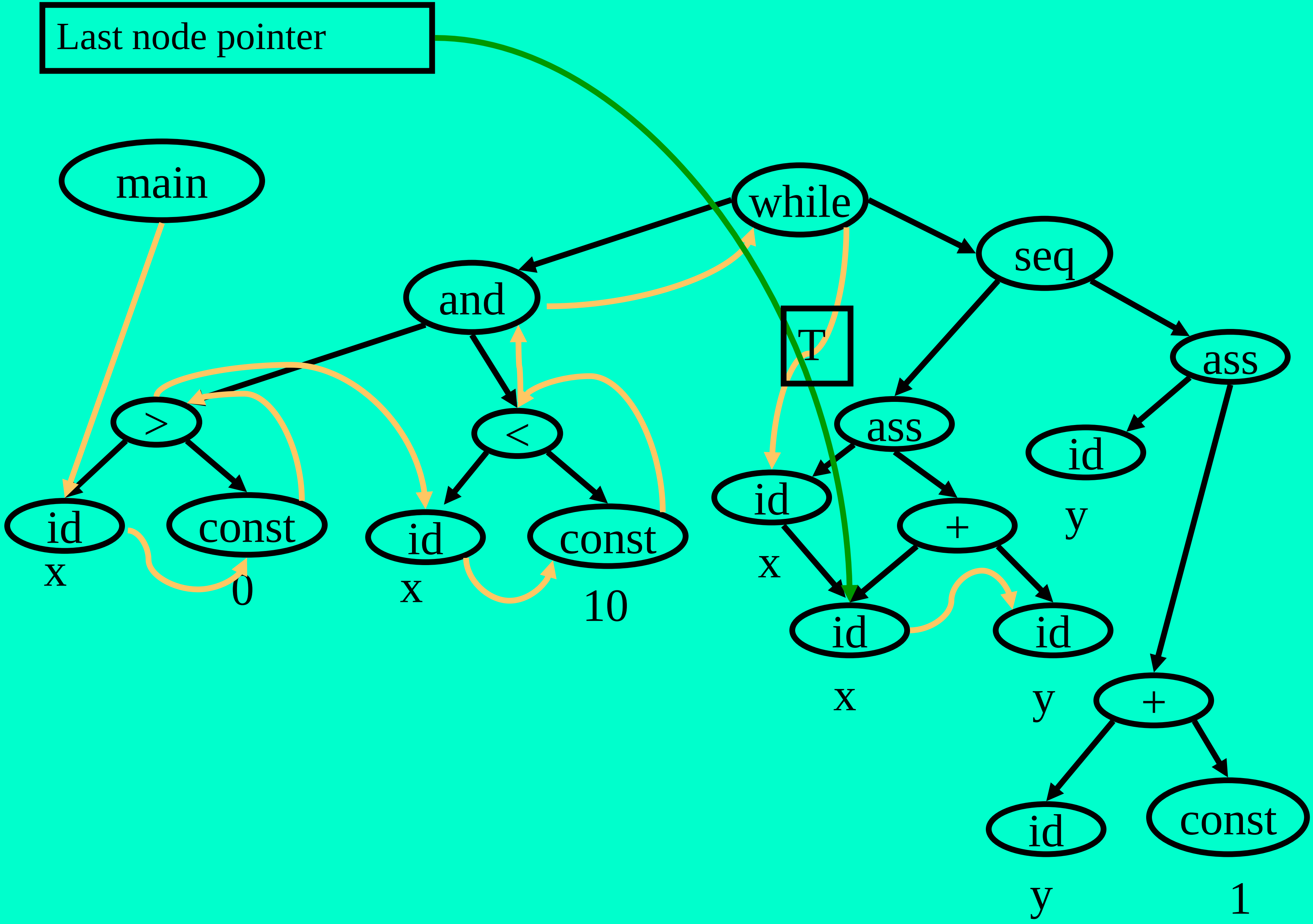
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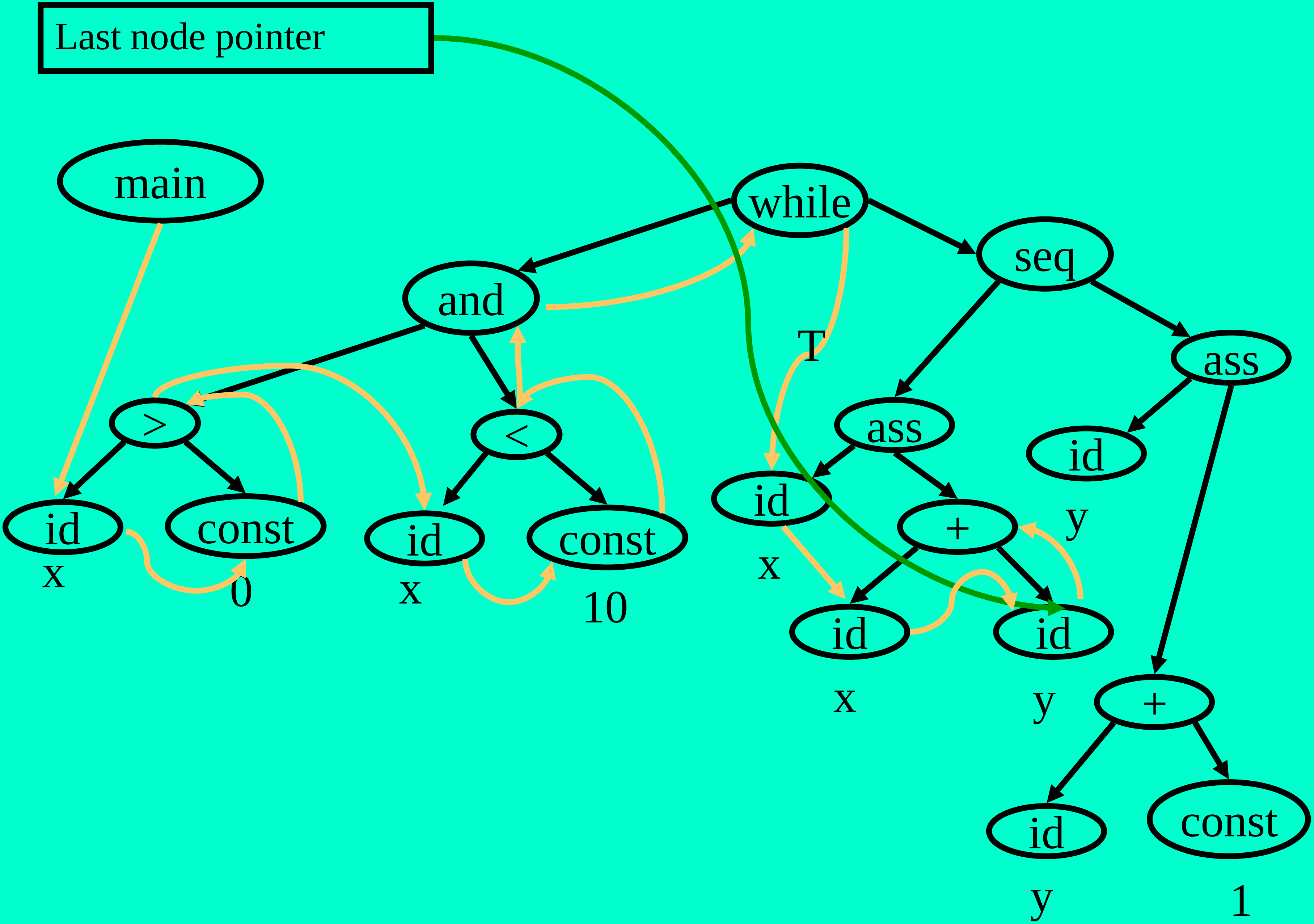
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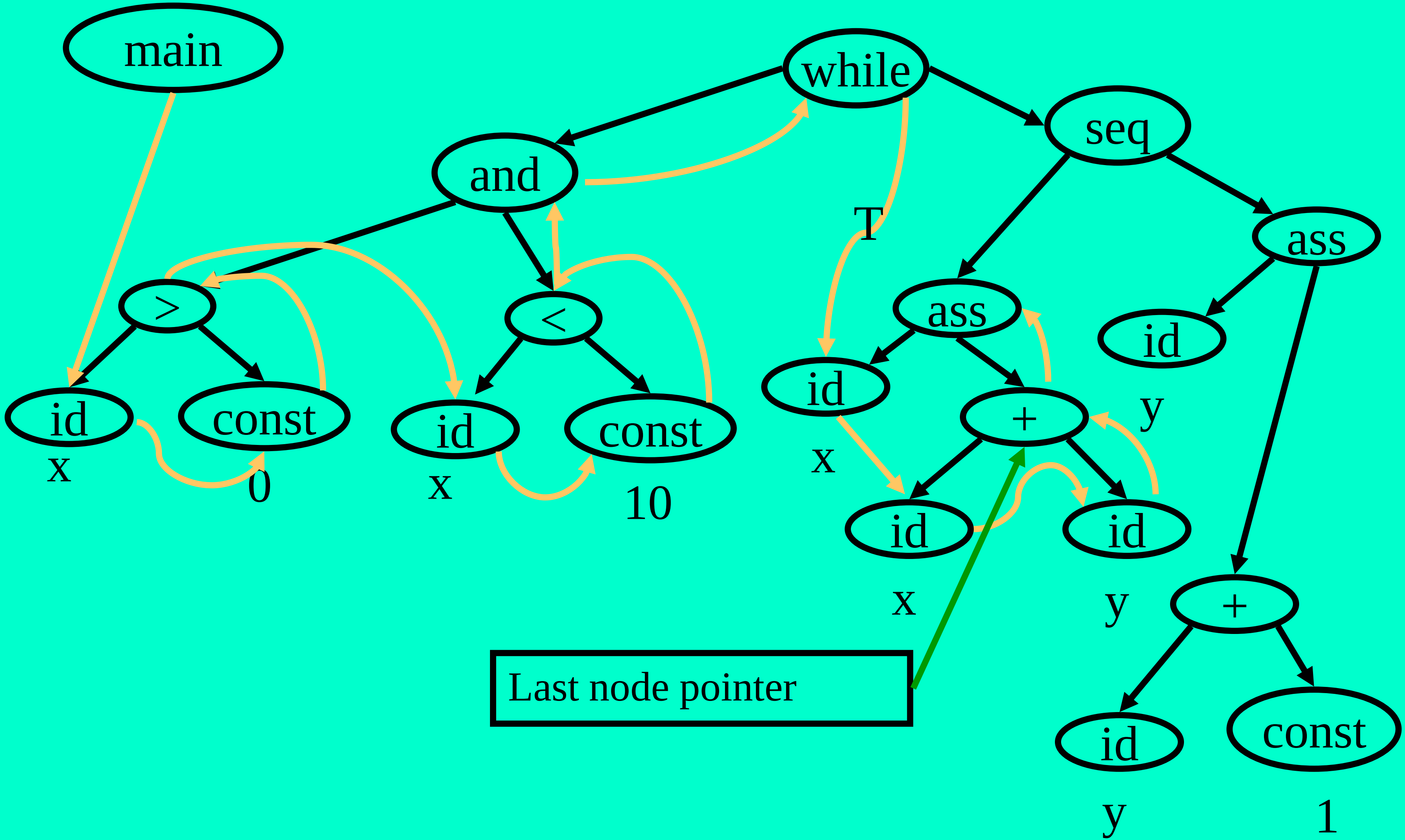
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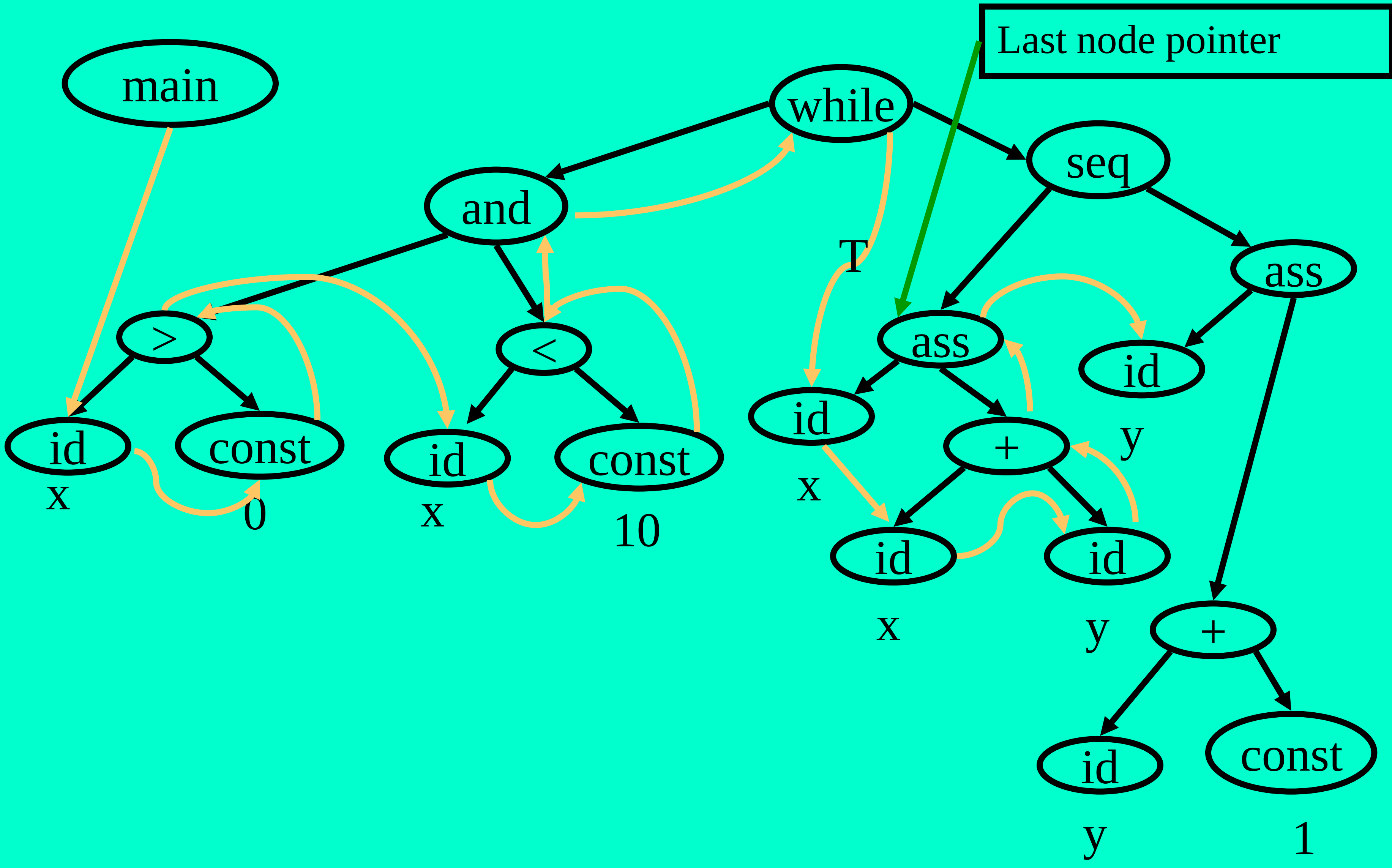
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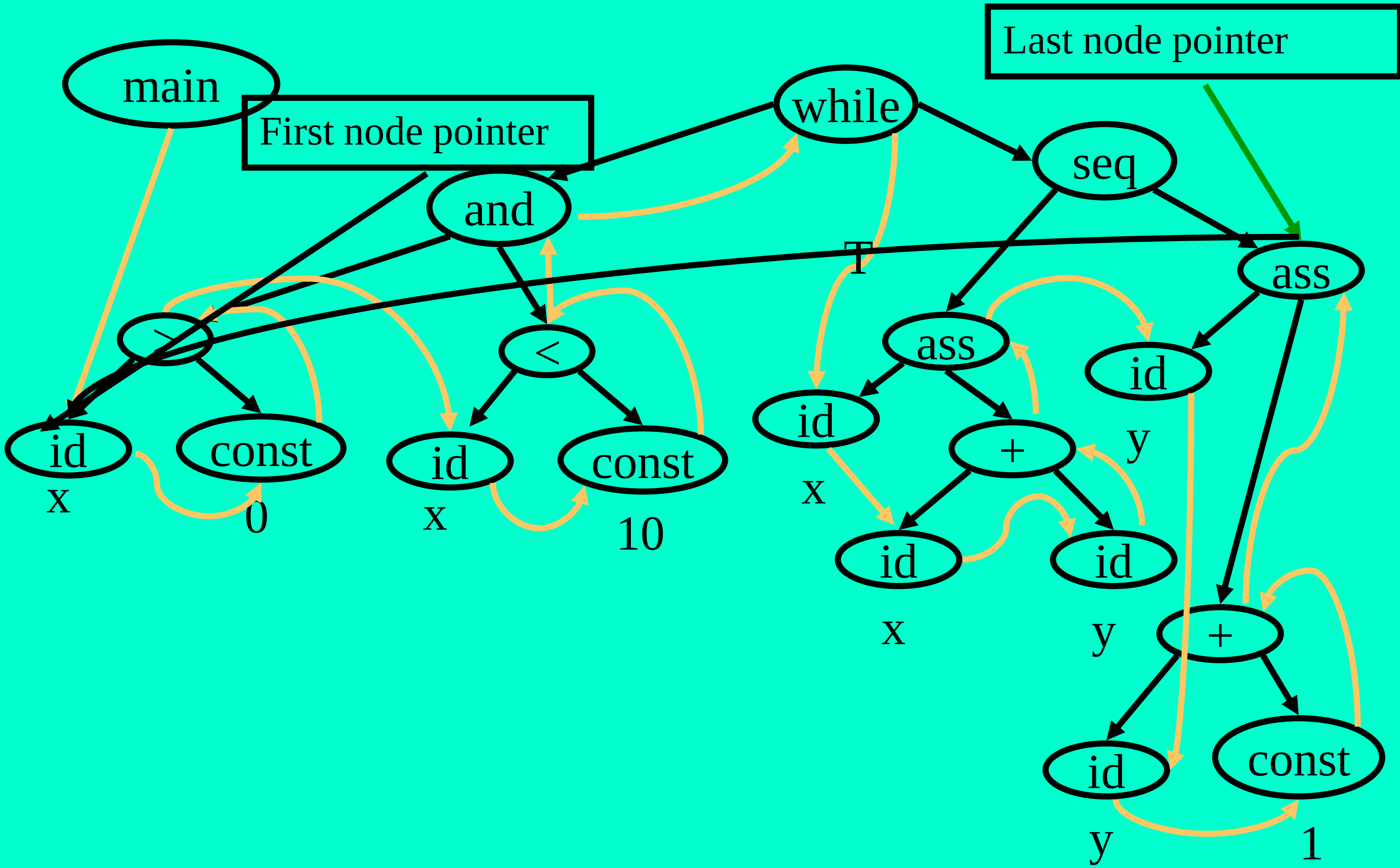
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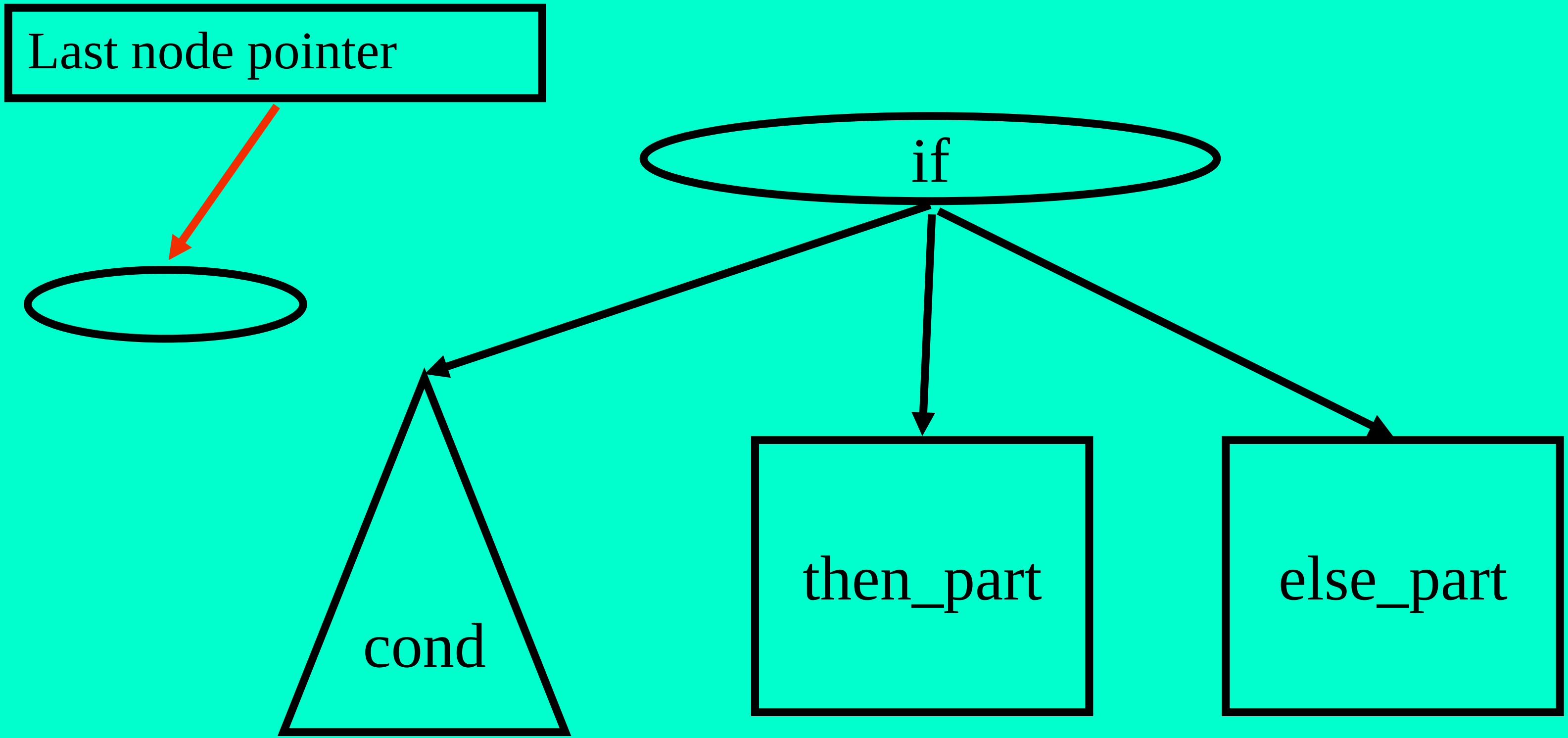
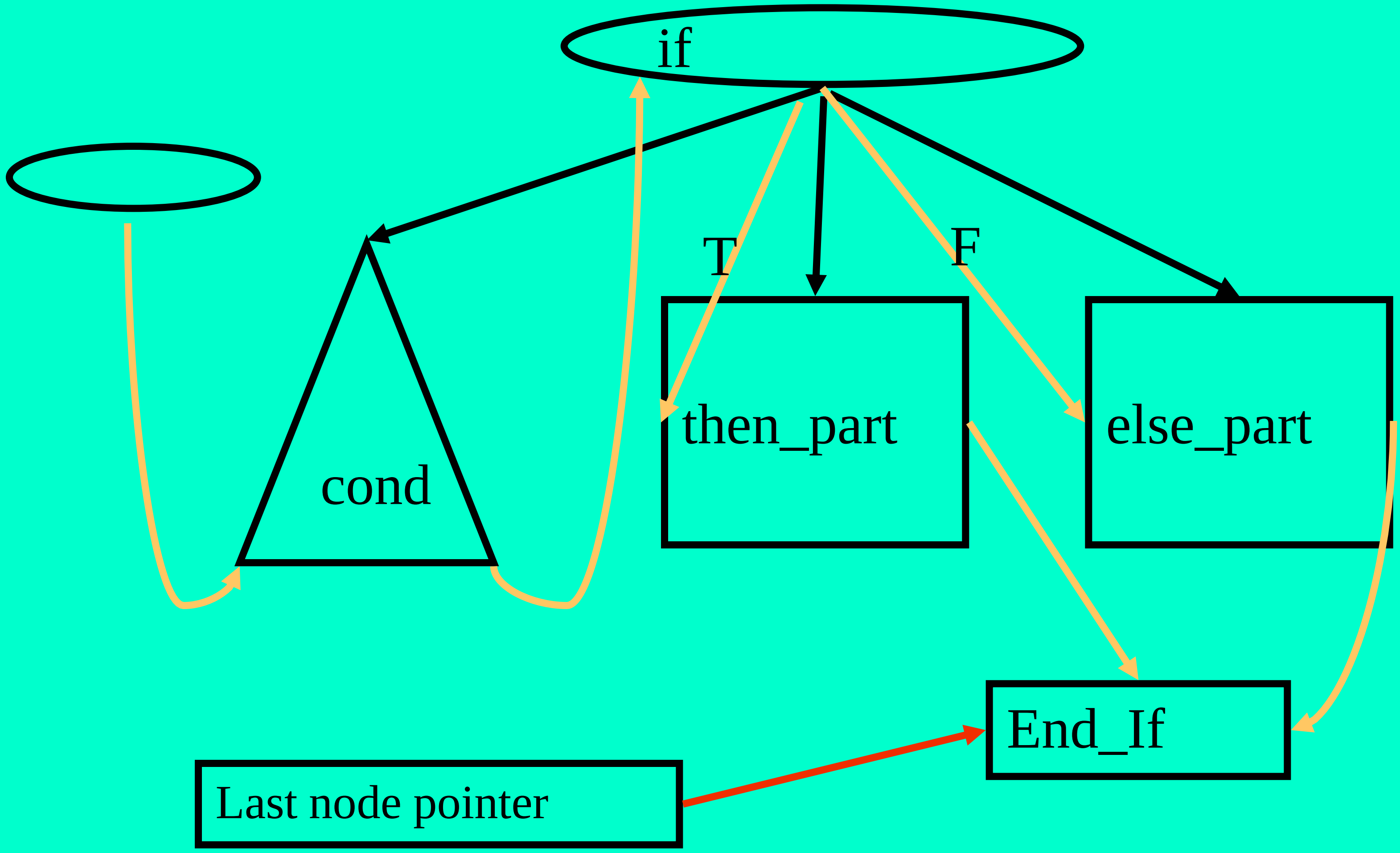
Demo Compiler

```
#include    "parser.h"      /* for types AST_node and Expression */
#include    "thread.h"      /* for self check */
                                        /* PRIVATE */
static AST_node *Last_node;

static void Thread_expression(Expression *expr) {
    switch (expr->type) {
    case 'D':
        Last_node->successor = expr; Last_node = expr;
        break;
    case 'P':
        Thread_expression(expr->left);
        Thread_expression(expr->right);
        Last_node->successor = expr; Last_node = expr;
        break;
    }
}
                                        /* PUBLIC */
AST_node *Thread_start;

void Thread_AST(AST_node *icode) {
    AST_node Dummy_node;

    Last_node = &Dummy_node; Thread_expression(icode);
    Last_node->successor = (AST_node *)0;
    Thread_start = Dummy_node.successor;
}
```

Conditional Statement



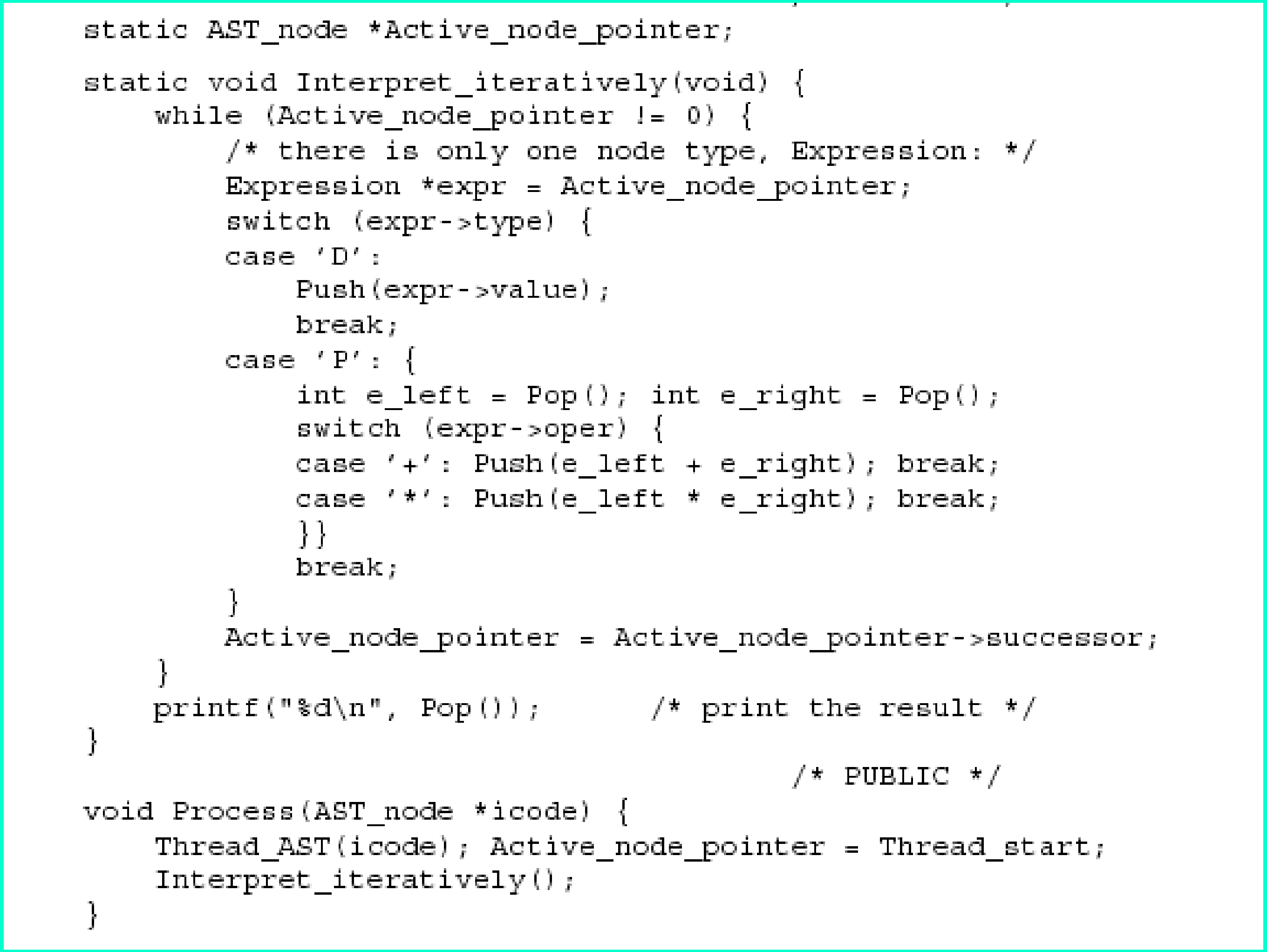
Conditional Statement



Iterative Interpretation

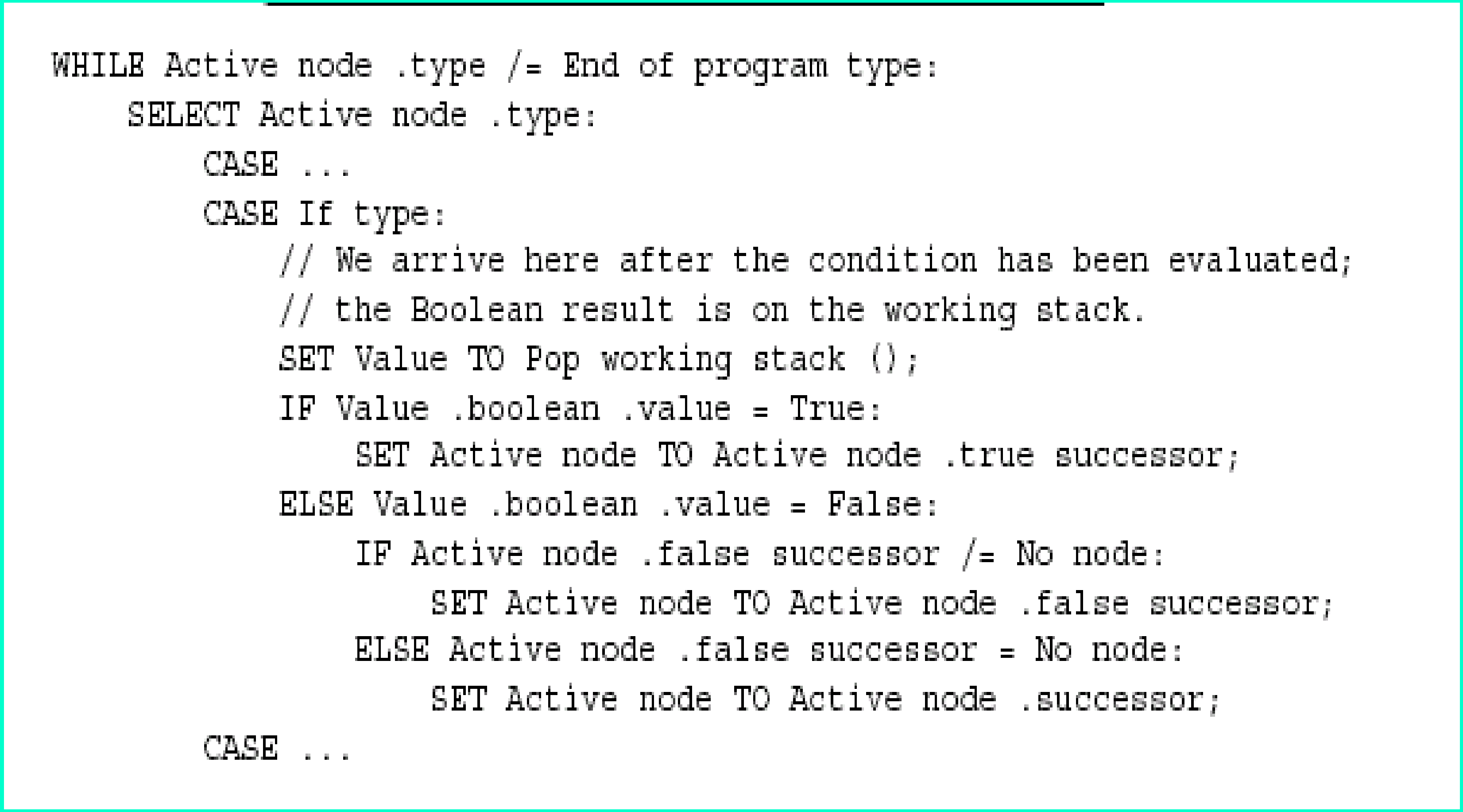
- Closed to CPU
- One flat loop with one big case statement
- Use explicit stack
  - Intermediate results
  - Local variables
- Requires fully annotated threaded AST
  - Active-node-pointer (interpreted node)

Demo Compiler



```
static AST_node *Active_node_pointer;

static void Interpret_iteratively(void) {
    while (Active_node_pointer != 0) {
        /* there is only one node type, Expression: */
        Expression *expr = Active_node_pointer;
        switch (expr->type) {
        case 'D':
            Push(expr->value);
            break;
        case 'P': {
            int e_left = Pop(); int e_right = Pop();
            switch (expr->oper) {
            case '+': Push(e_left + e_right); break;
            case '*': Push(e_left * e_right); break;
            }}
            break;
        }
        Active_node_pointer = Active_node_pointer->successor;
    }
    printf("%d\n", Pop());      /* print the result */
}
                                        /* PUBLIC */
void Process(AST_node *icode) {
    Thread_AST(icode); Active_node_pointer = Thread_start;
    Interpret_iteratively();
}
```

Conditional Statements

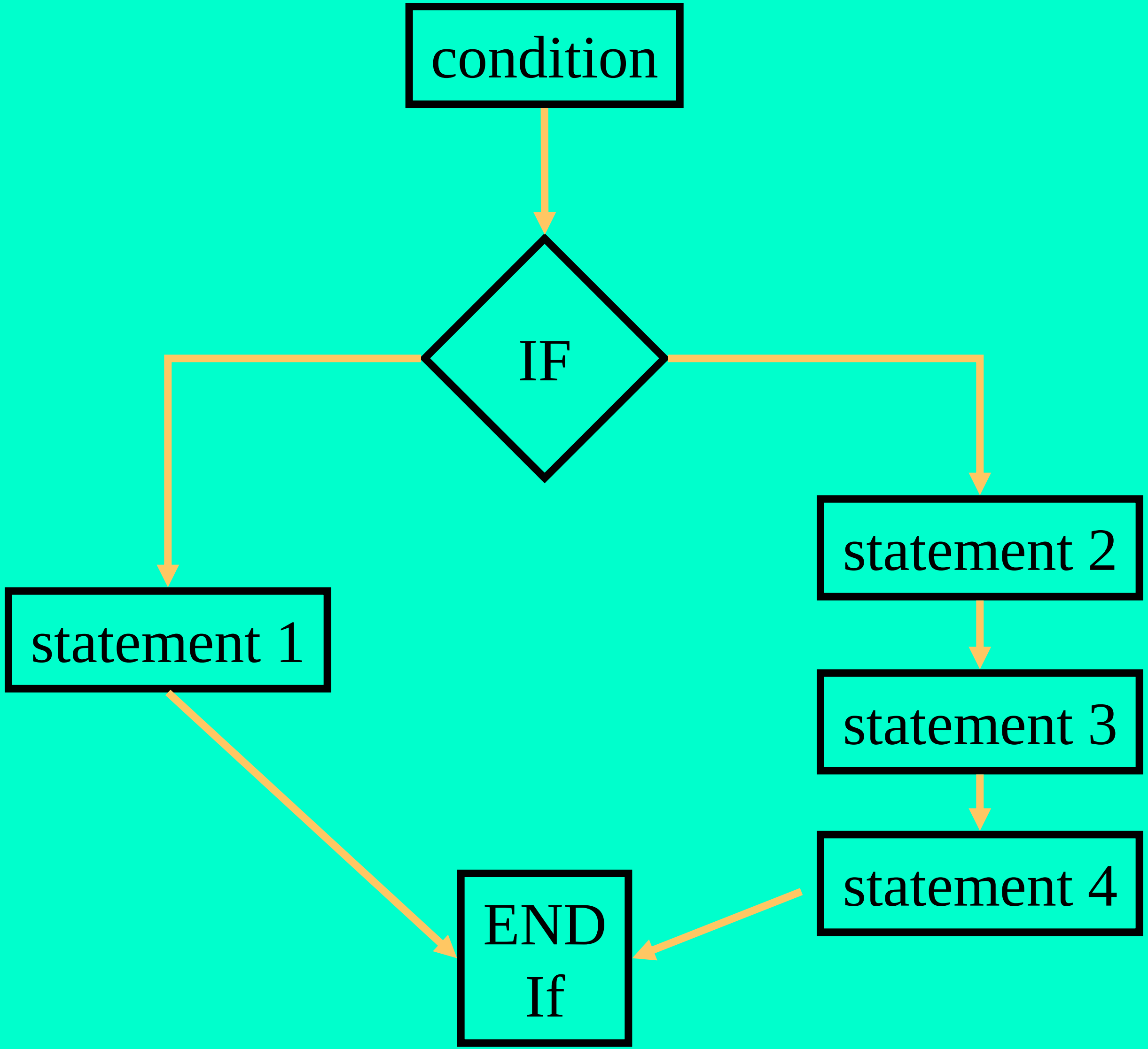


```
WHILE Active node .type /= End of program type:
    SELECT Active node .type:
        CASE ...
        CASE If type:
            // We arrive here after the condition has been evaluated;
            // the Boolean result is on the working stack.
            SET Value TO Pop working stack ();
            IF Value .boolean .value = True:
                SET Active node TO Active node .true successor;
            ELSE Value .boolean .value = False:
                IF Active node .false successor /= No node:
                    SET Active node TO Active node .false successor;
                ELSE Active node .false successor = No node:
                    SET Active node TO Active node .successor;
        CASE ...
```

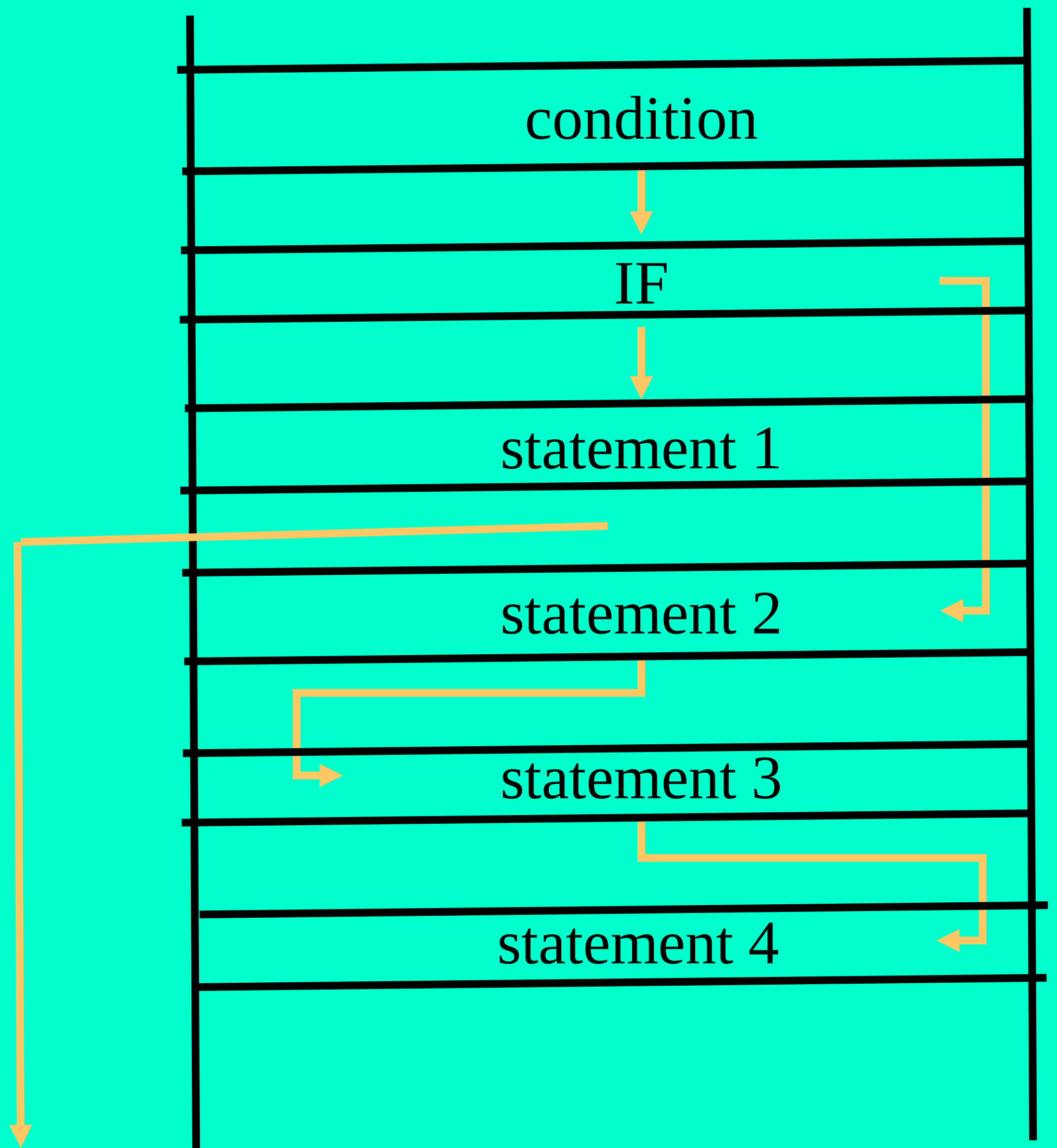
Storing Threaded AST

- General Graph
- Array
- Pseudo Instructions

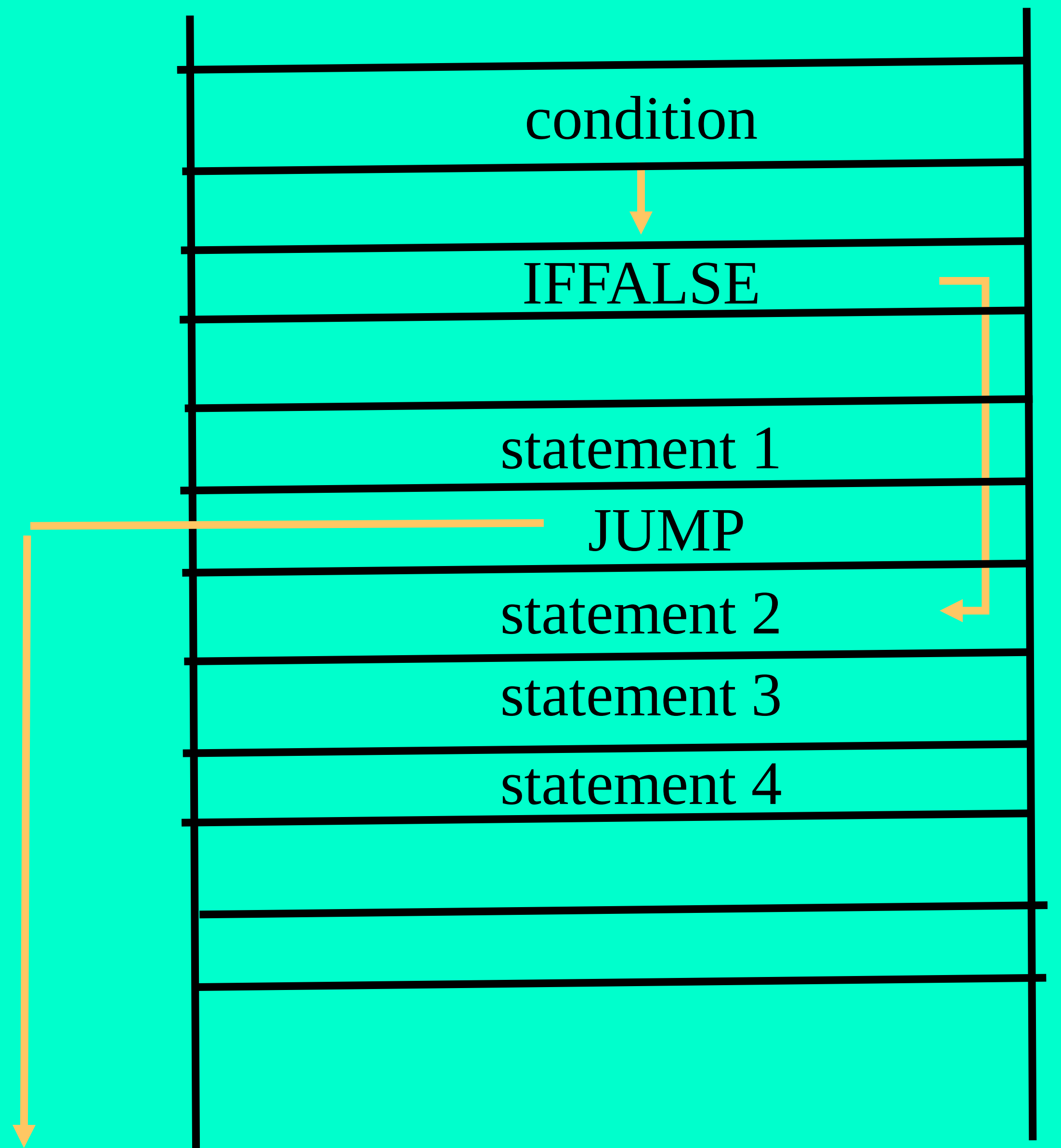
Threaded AST as General Graph



Threaded AST as Array



Threaded AST as Pseudo Instructions



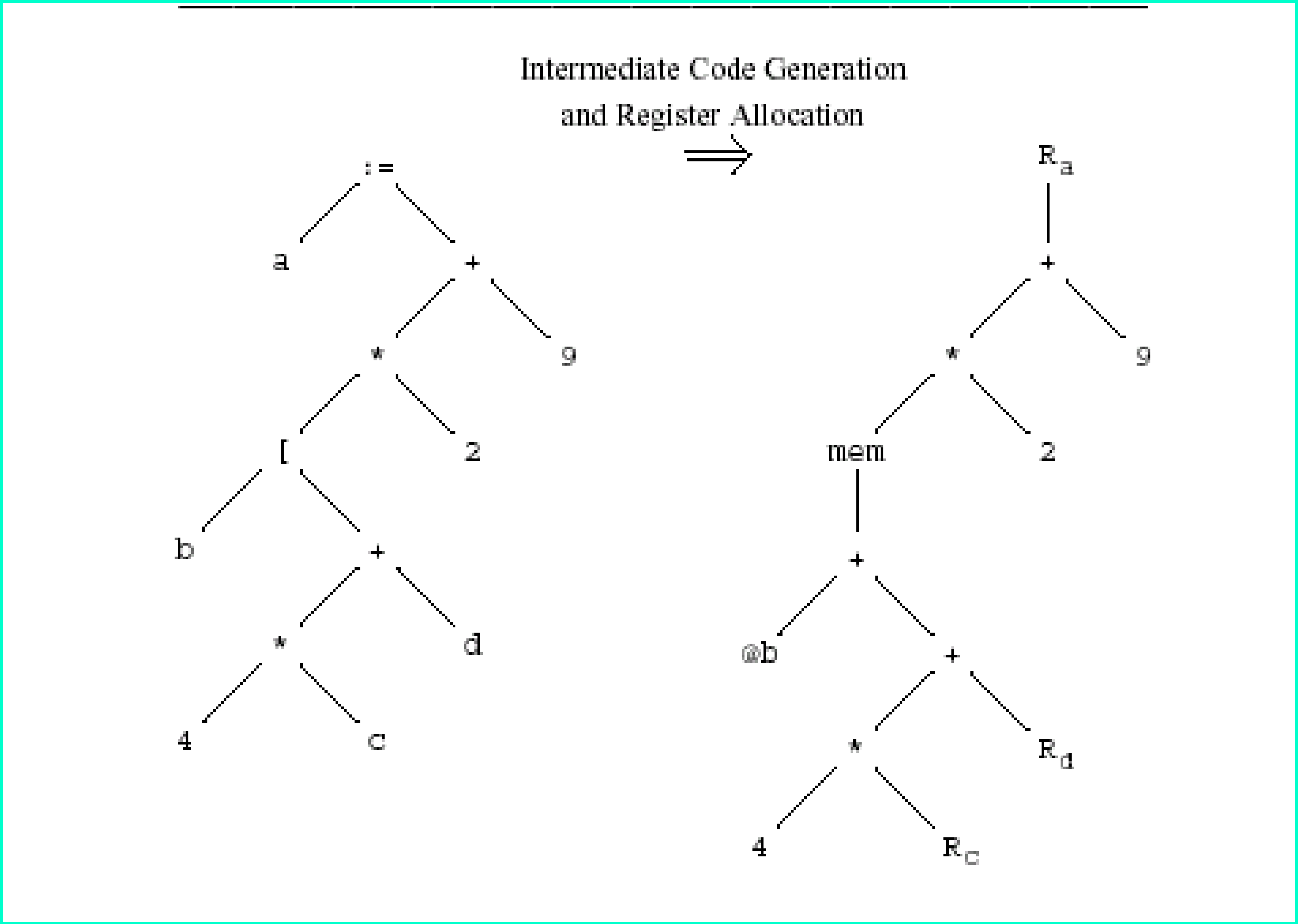
Iterative Interpreters (Summary)

- Different AST representations
- Faster than recursive interpreters
  - Some interpretative overhead is eliminated
- Portable
- Secure
- Similarities with the compiler

Code Generation

- Transform the AST into machine code
- Machine instructions can be described by tree patterns
- Replace tree-nodes by machine instruction
  - Tree rewriting
  - Replace subtrees
- Applicable beyond compilers

a := (b[4*c+d]*2)+9



Intermediate Code Generation
and Register Allocation
:=
a
+
*
9
[
2
b
+
*
d
4
c
R_a
+
*
9
mem
2
+
@b
+
*
R_d
4
R_c

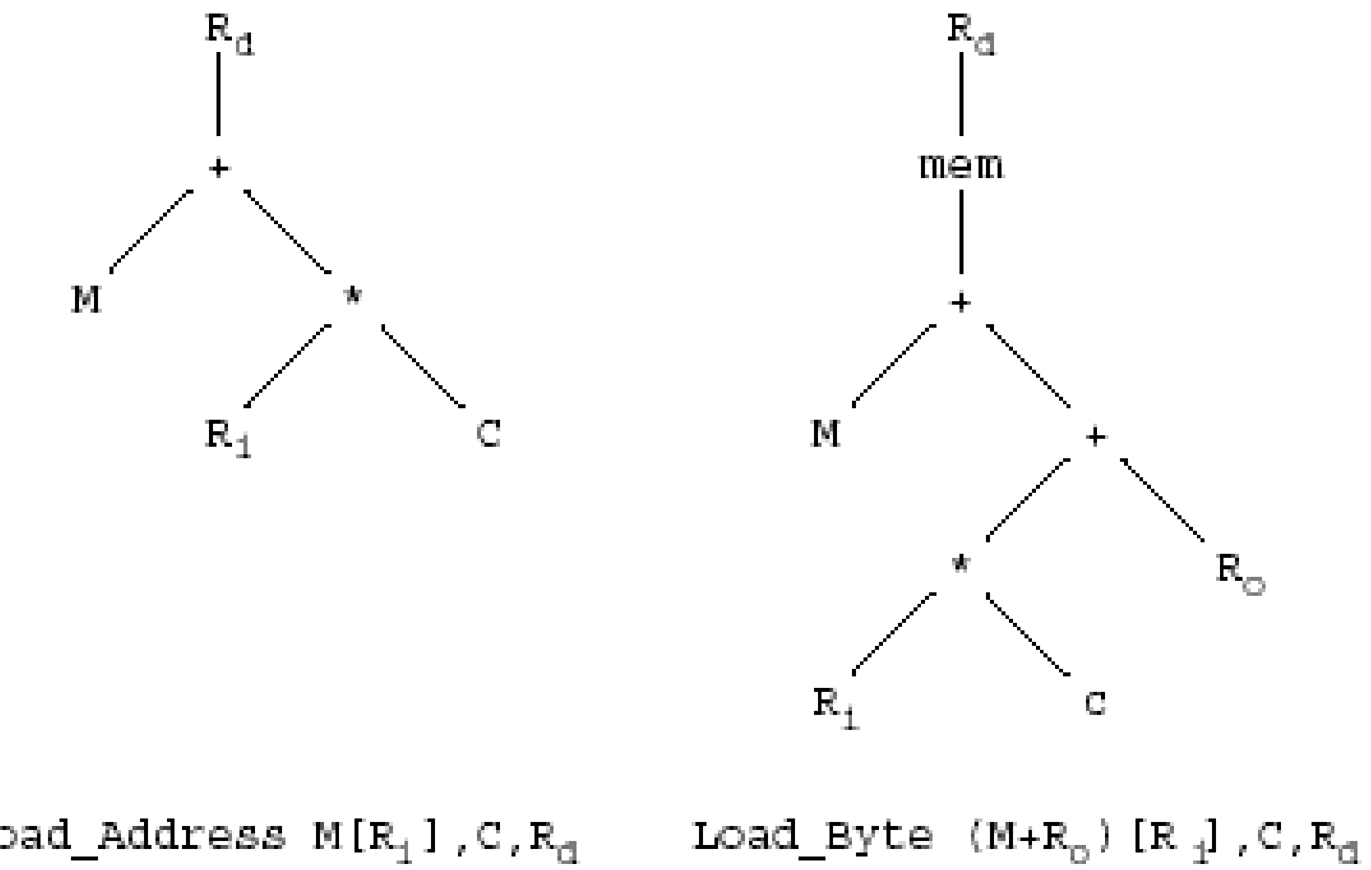
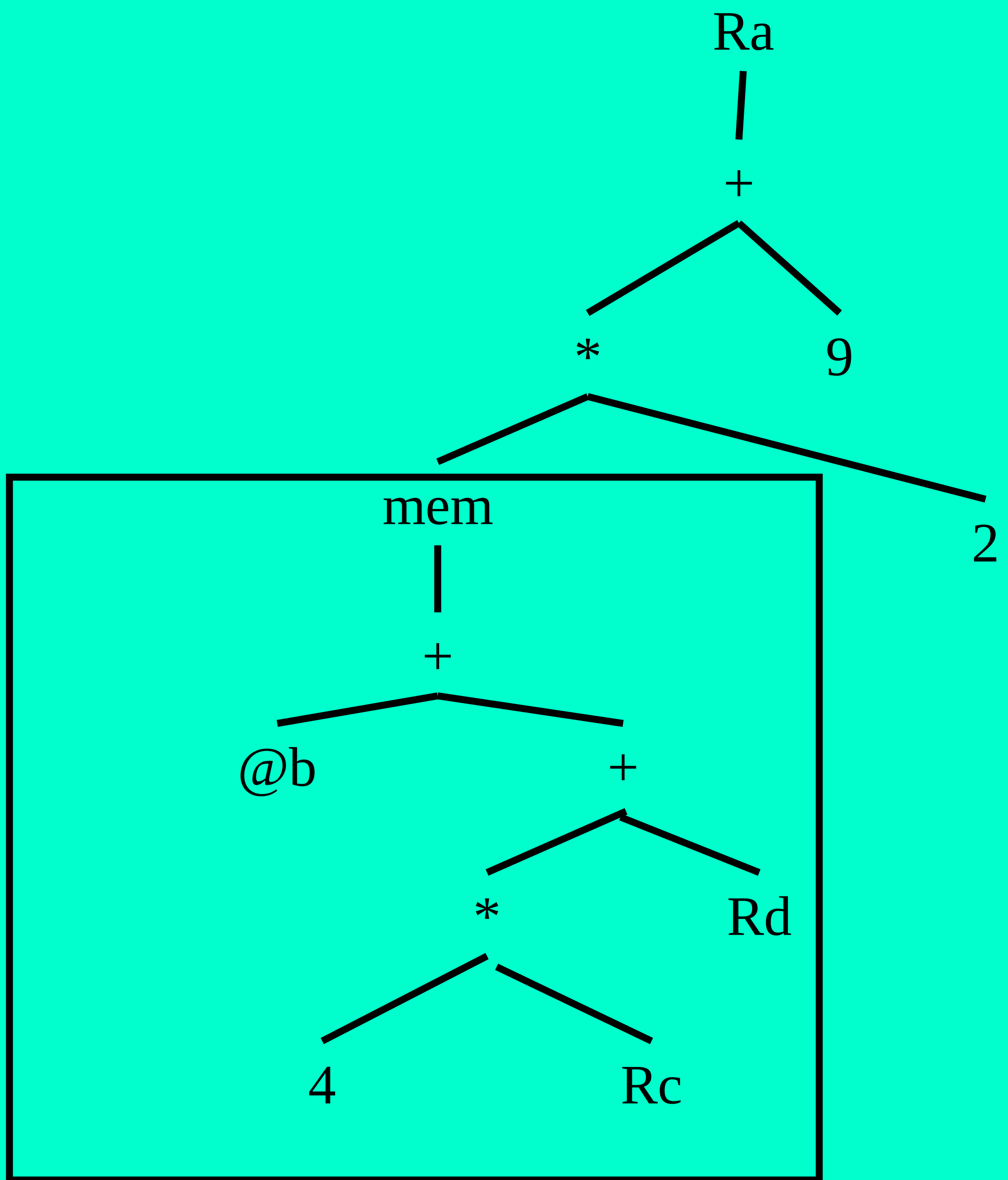
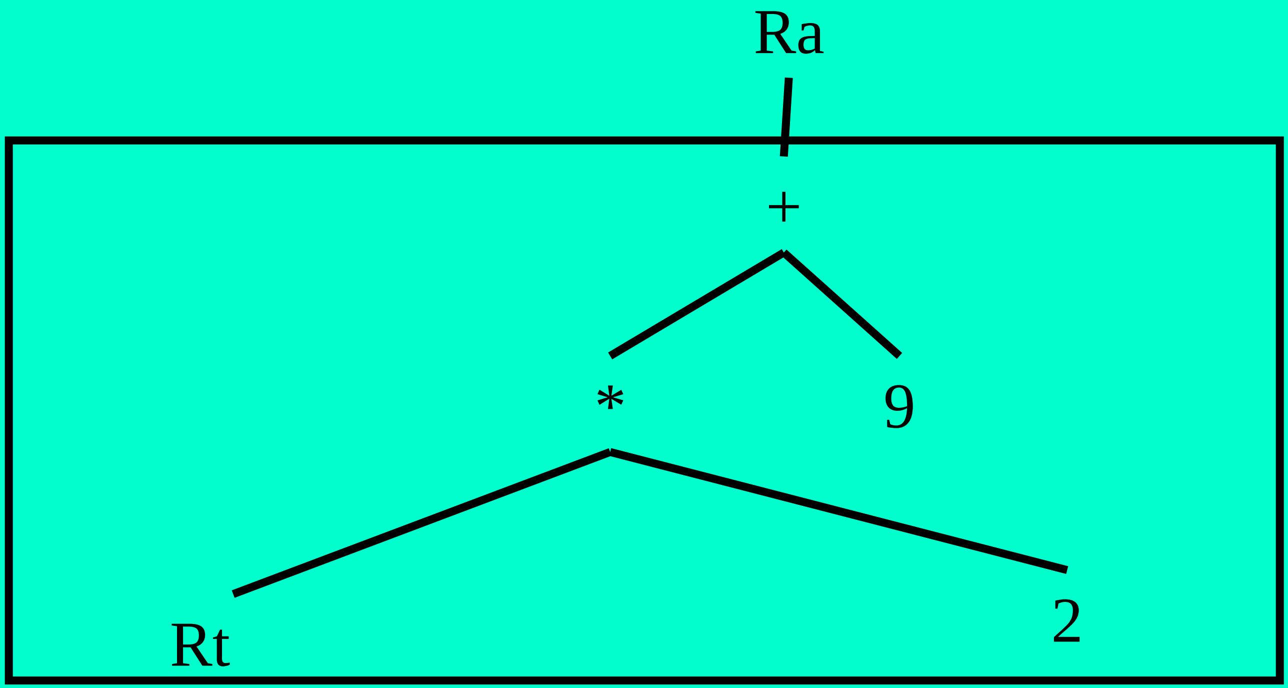

R_d
+
M
*
R_i
C
Load_Address M[R_i],C,R_d
R_d
mem
+
M
+
*
R_o
R_i
C
Load_Byte (M+R_o)[R_i],C,R_d

Figure 4.10 Two sample instructions with their ASTs.

leal movsbl


Ra
+
*
9
mem
2
+
@b
+
*
Rd
4
Rc



Load_Byte (b+Rd)[Rc], 4, Rt

$$\begin{tikzcd}
& \text{Ra} \arrow[d, dash] \\
& \text{Load\_address 9[Rt], 2, Ra} \arrow[dl, dash] \\
\text{Load\_Byte (b+Rd)[Rc], 4, Rt} &
\end{tikzcd}$$

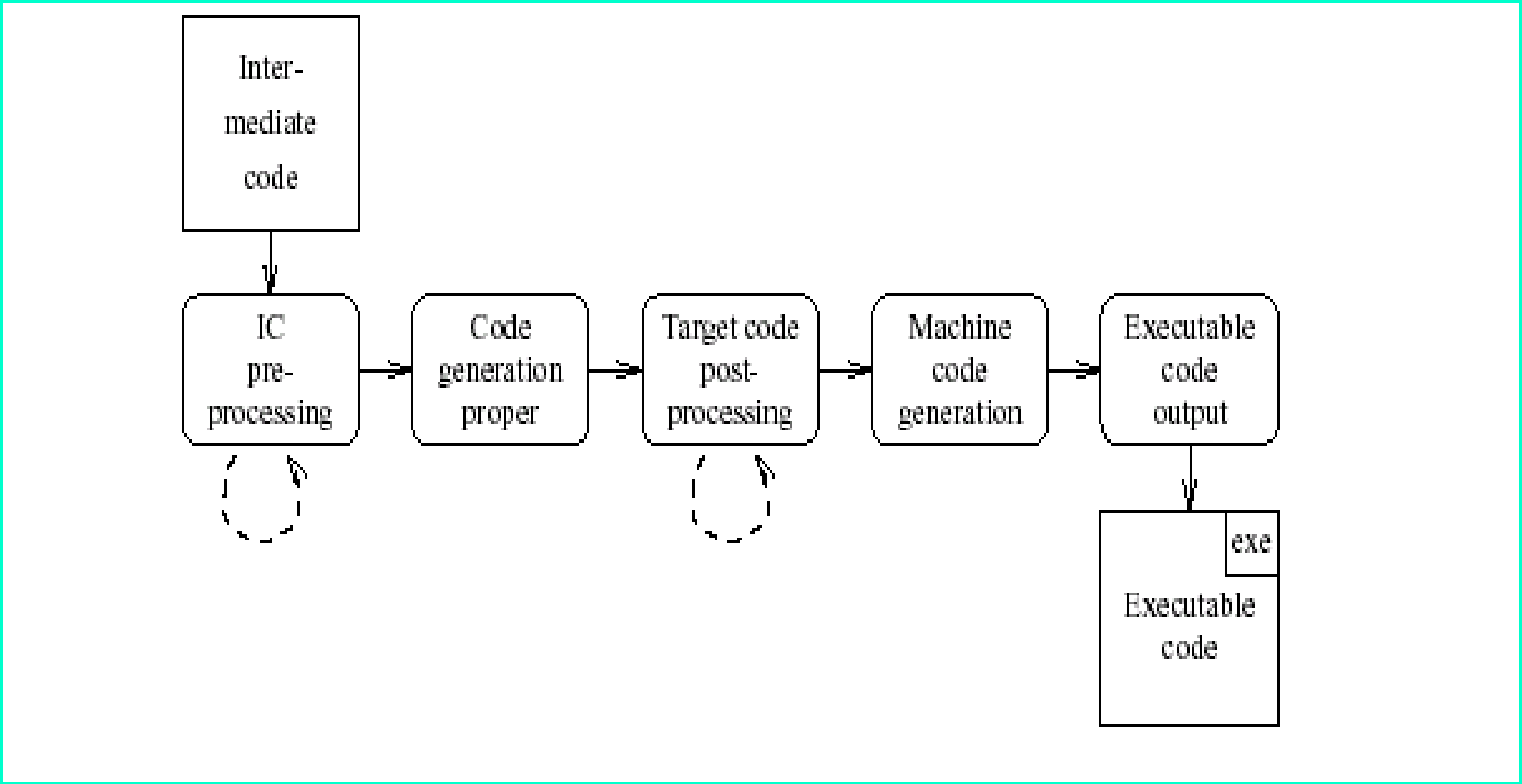
Code generation issues

- Code selection
- Register allocation
- Instruction ordering

Simplifications

- Consider small parts of AST at time
- Simplify target machine
- Use simplifying conventions

Overall Structure



Inter-mediate code
IC pre-processing
Code generation proper
Target code post-processing
Machine code generation
Executable code output
exe
Executable code