COMPILER DESIGN

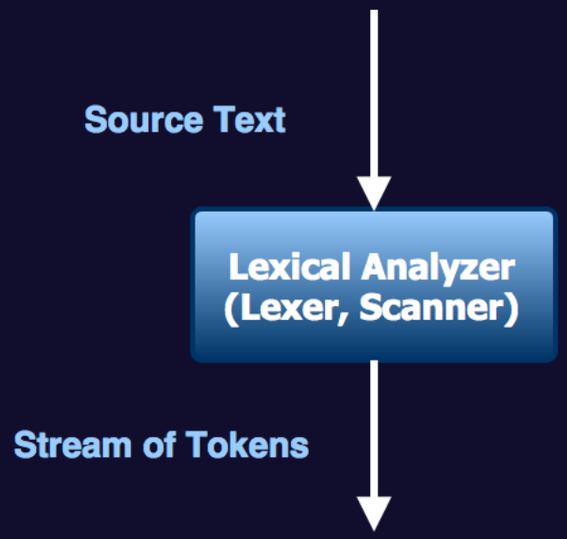
AND IMPLEMENTATION

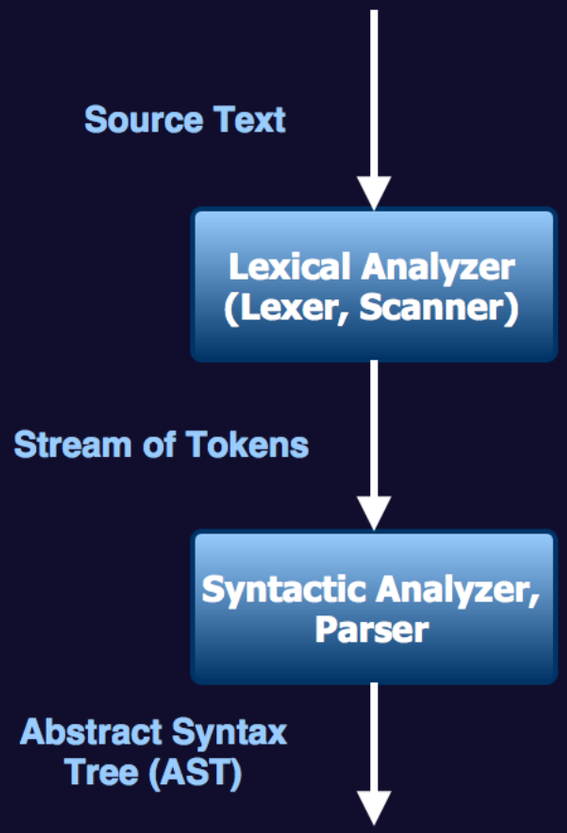
ÁRPÁD GORETITY
BUDAPEST SWIFT MEETUP

CODE GENERATION

PART 4

REMINDER


Source Text
Lexical Analyzer
(Lexer, Scanner)
Stream of Tokens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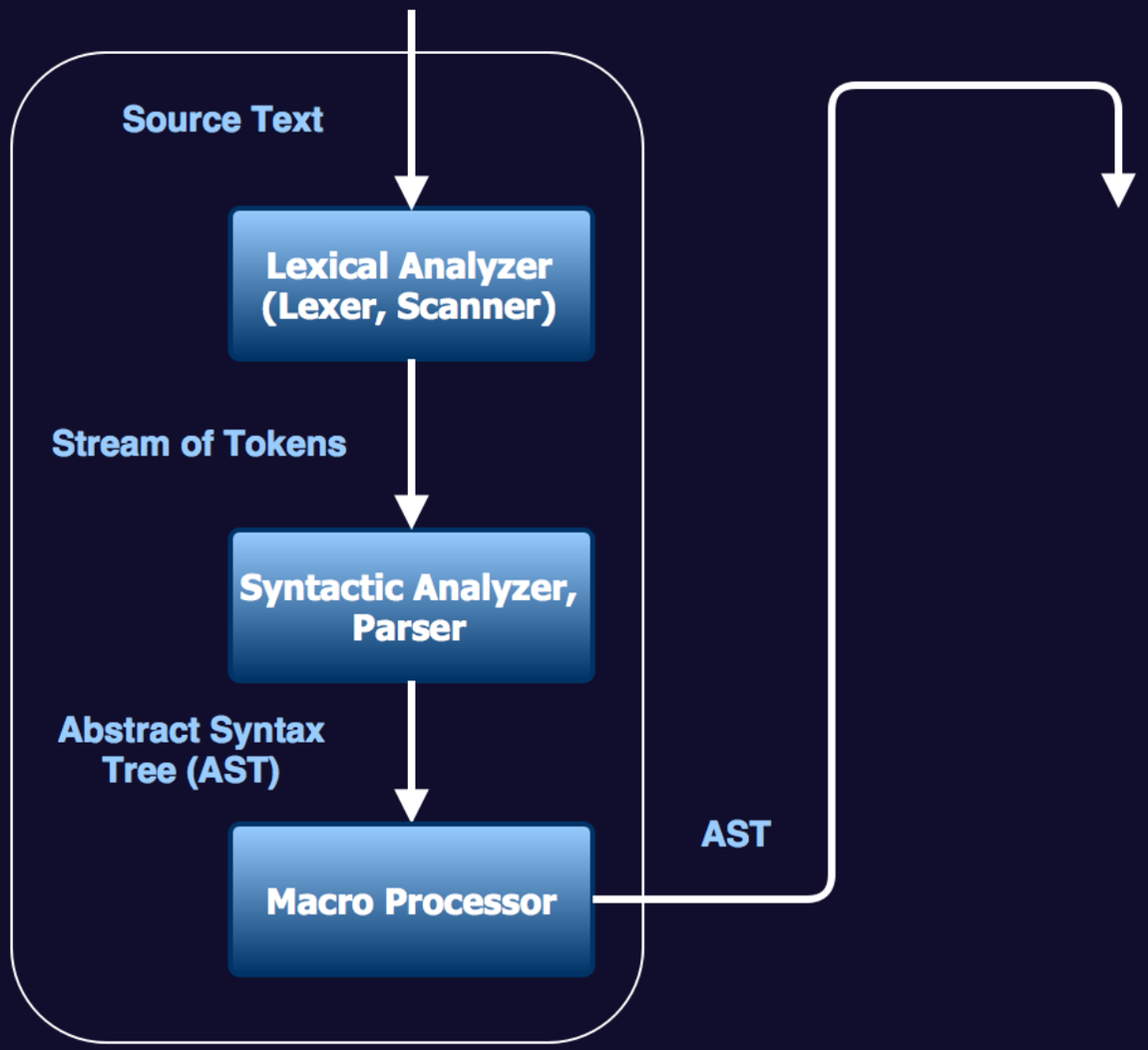
Syntactic Analyzer, Parser
Abstract Syntax Tree (AST)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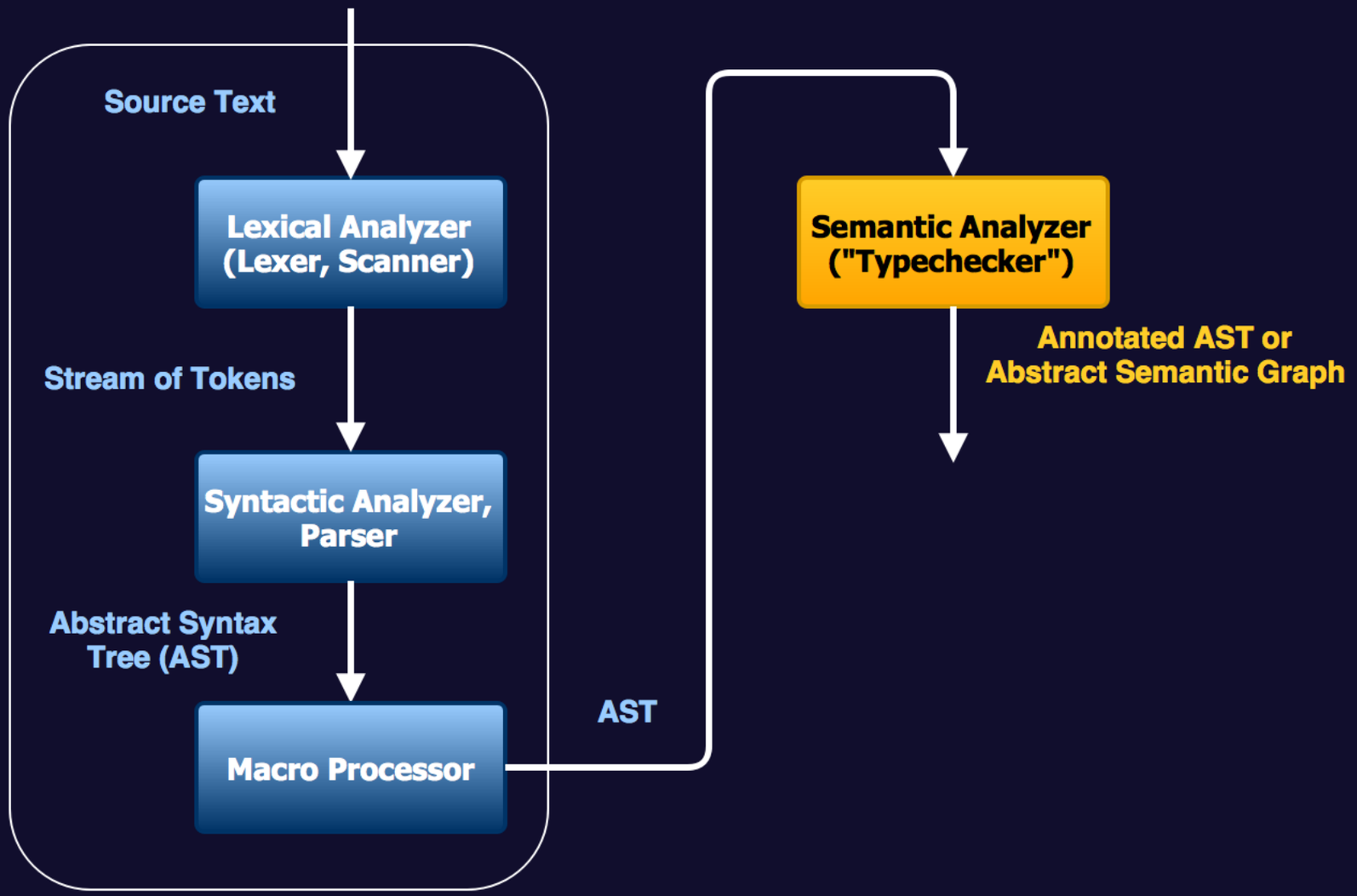
Macro Processor
AST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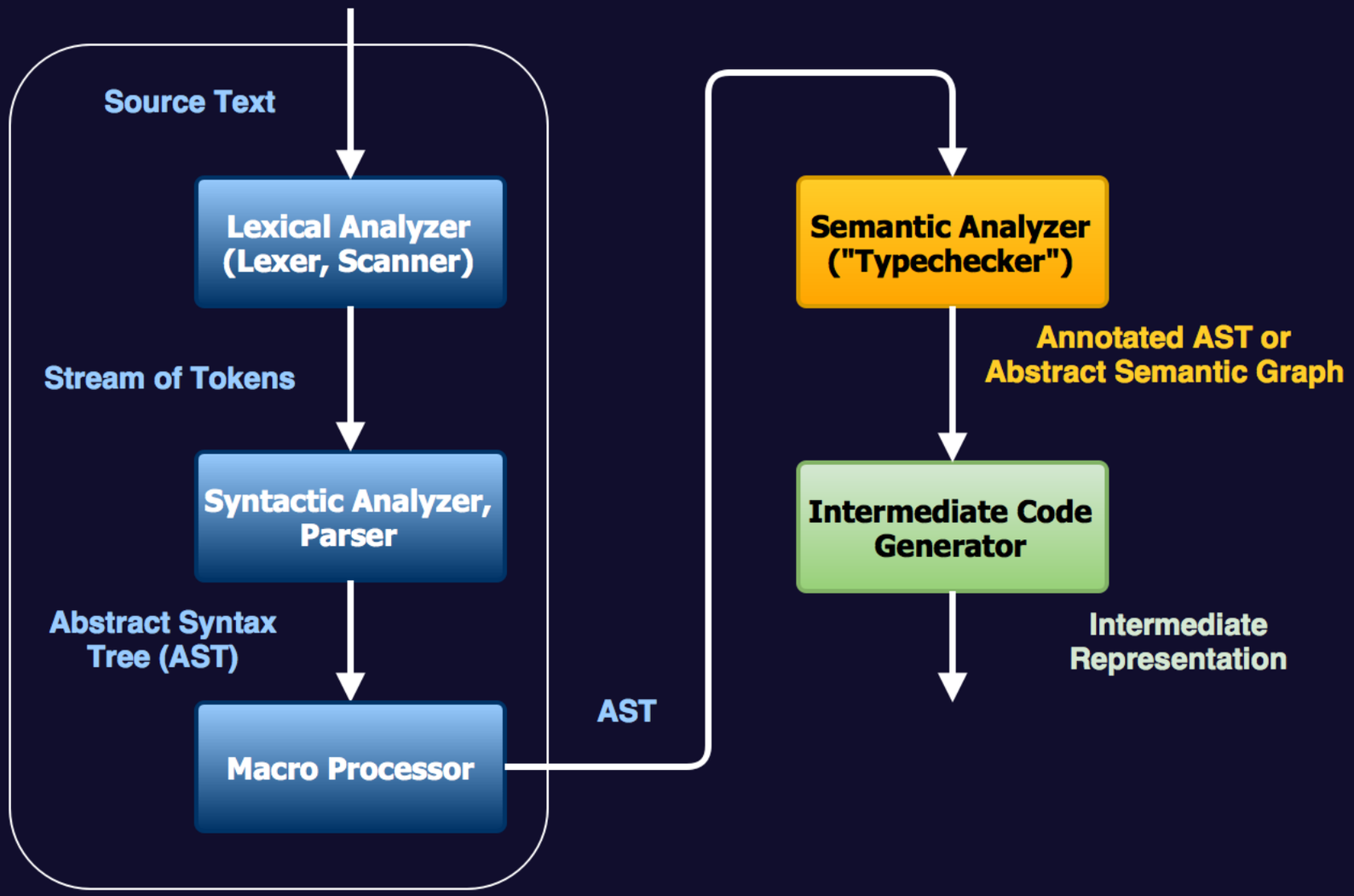
("Typechecker")
Annotated AST or
Abstract Semantic Graph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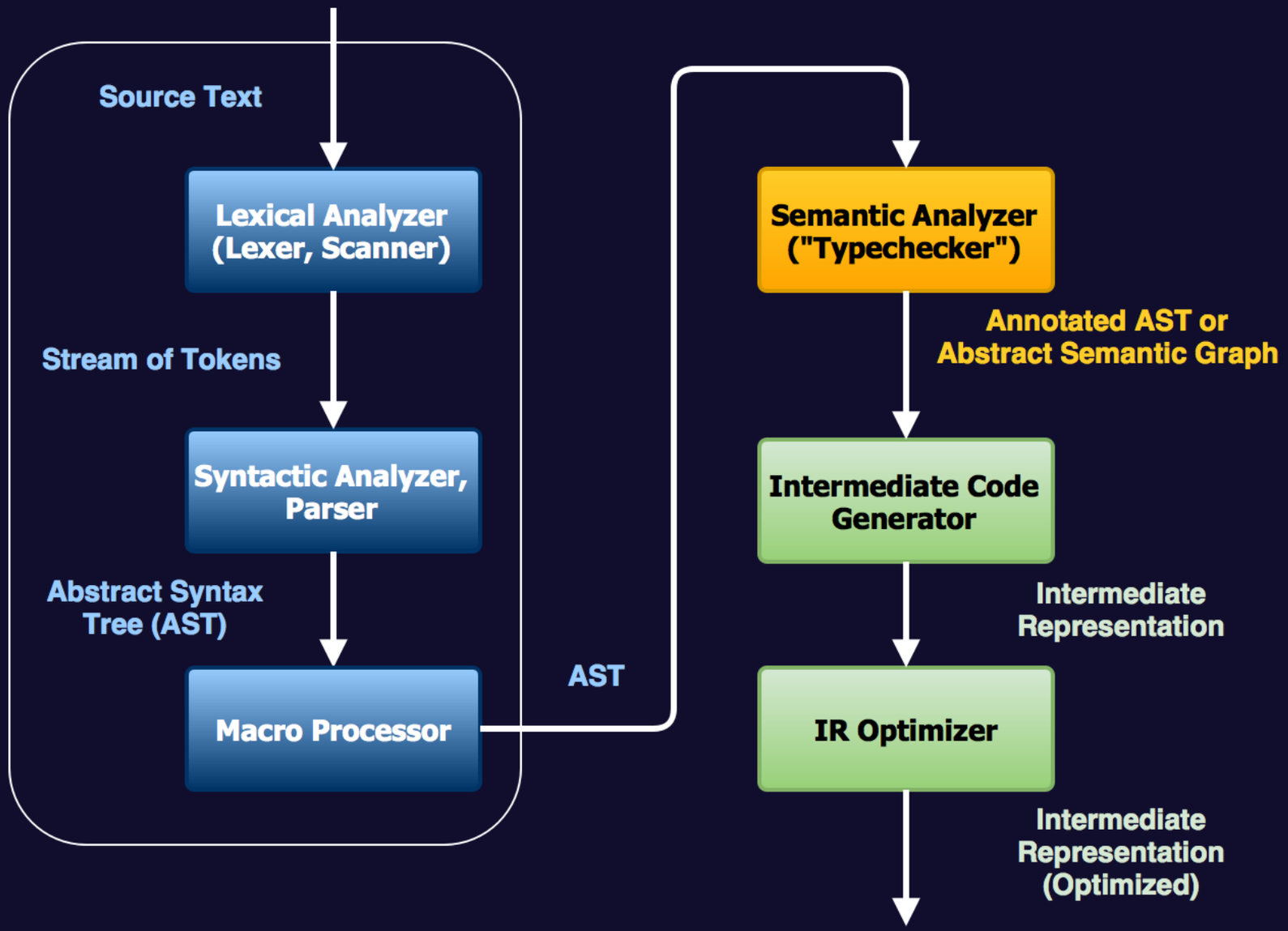
Intermediate Representation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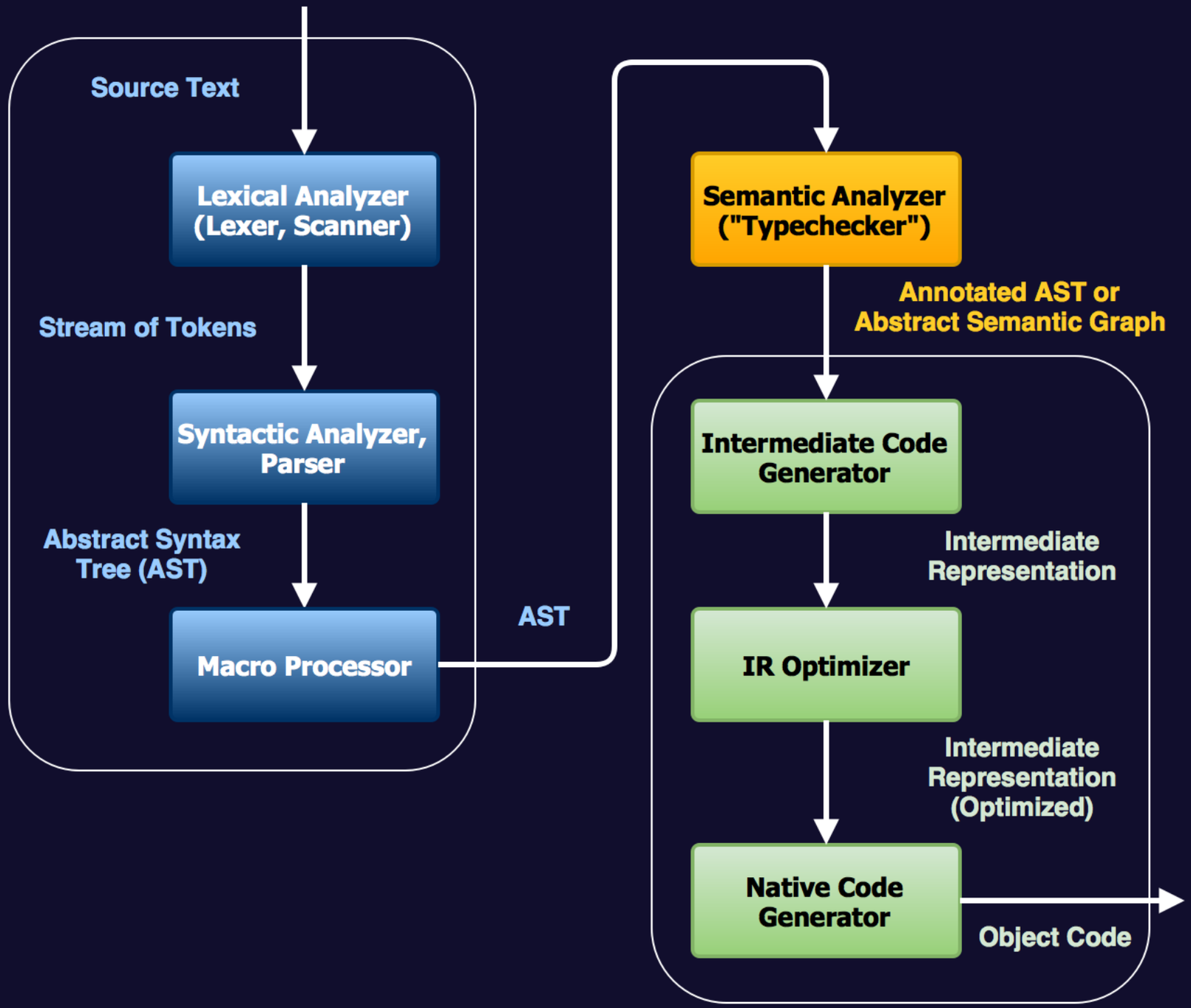
IR Optimizer
Intermediate Representation (Optimized)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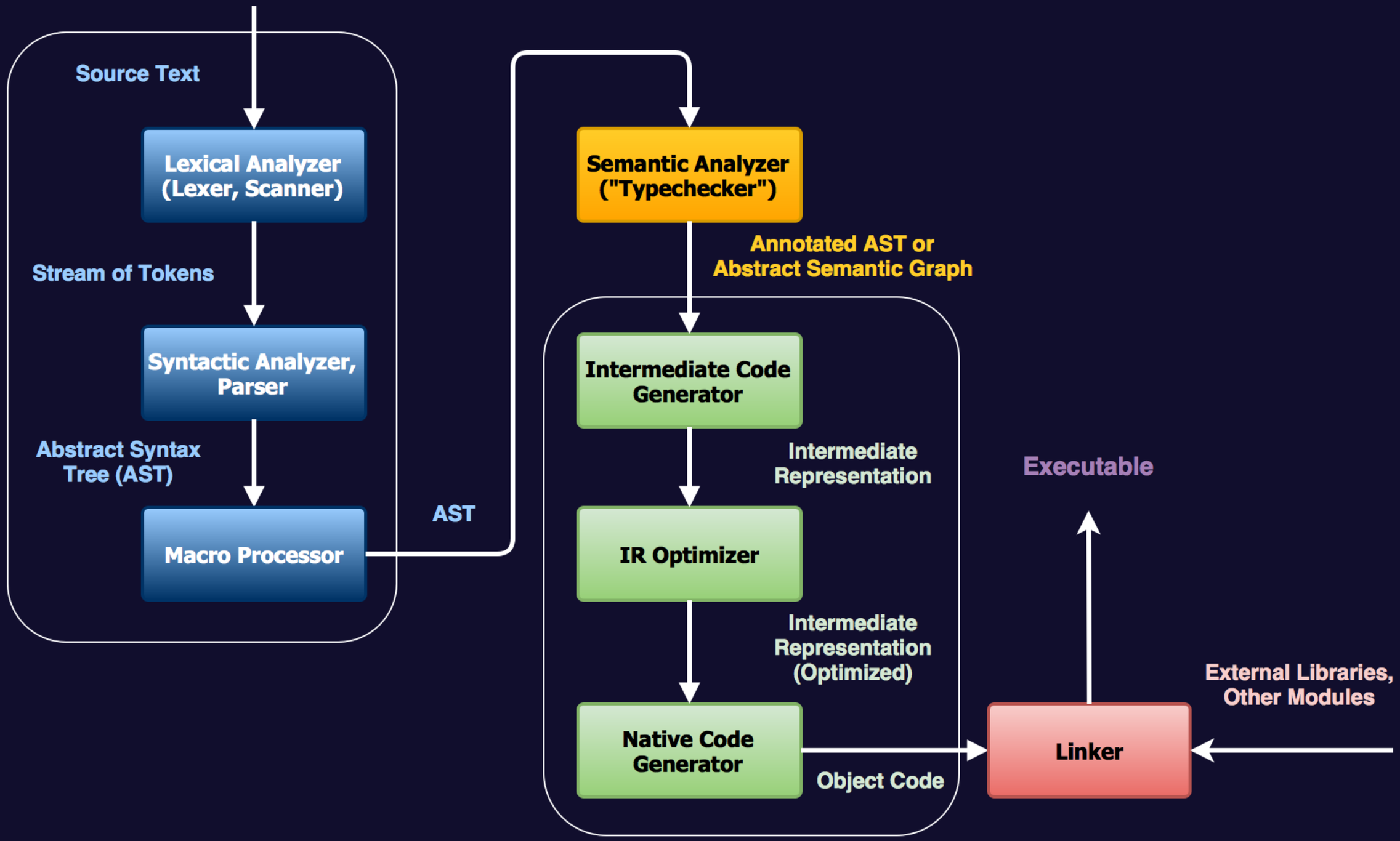
IR Optimizer
Intermediate Representation (Optimized)
Native Code Generator
Object Code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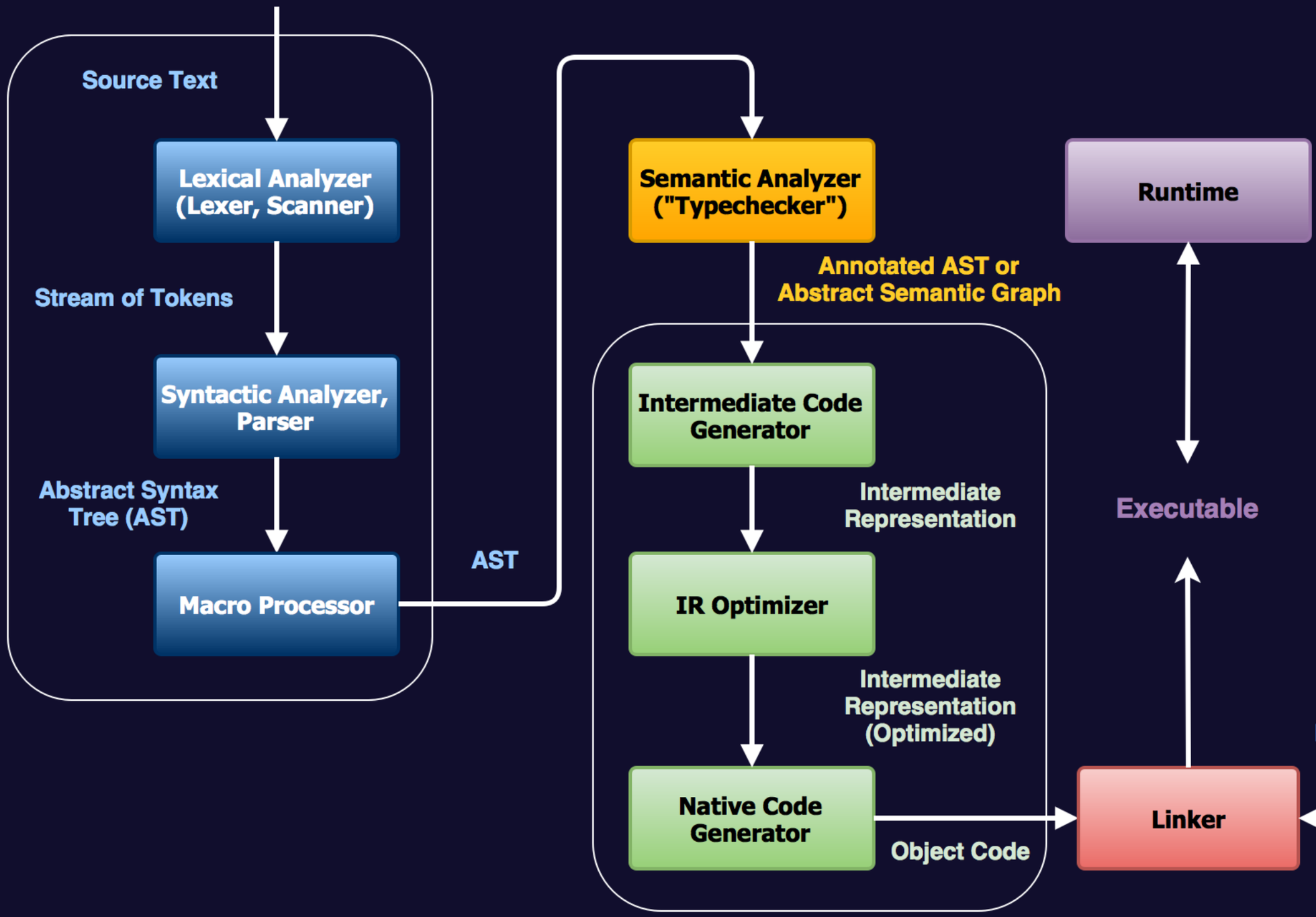
Native Code Generator
Object Code
Linker
Executable
External Libraries, Other Modules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Intermediate Representation (Optimized)
Native Code Generator
Object Code
Runtime
Executable
Linker
External Libraries, Other Modules

REMINDER

- Semantic Analysis
  - Input: AST
  - Output: IR (high-level or low-level)
- If succeeds: program "makes sense"
  - At this point, abstractions are ready to be collapsed into executable code

CODE GENERATION

- Process that transforms language-dependent IR into language-agnostic executable code
  - Directly binary machine code: rare, e.g. TCC
  - Assembly: was very popular, e.g. GCC
  - Low-level but machine-independent IR: e.g. Clang
    - Most popular: LLVM

OH NOES, NOT ANOTHER IR!

- Machine-independent, yet low-level optimizations
- Native code generation –> **Some** of ABI abstracted away
- Linker support (native and IR)
  - Opportunity for intermodule optimization, "LTO"
    - Not possible or very hard in native code
- Many languages, same back-end –> less work

THE LLVM COMPILER INFRASTRUCTURE

- IR with 3 first-class representations
  - Binary "bitcode"; Textual "assembly"; C++ objects
- Division of labor – beneficial for compiler writers:
  - Front- / middle-end: generate LLVM IR
  - LLVM: heavy lifting (optimization, native codegen)
  - Implementing the Runtime: still our duty…

LLVM IR

- High-level model of a modern von Neumann architecture
  - Registers – arbitrarily many
  - Memory – explicitly allocated, implicitly deallocated (stack)
    - Explicit loads and stores – Stateful
    - Pointer arithmetic
- Control flow model: Control Flow Graph and Functions
- Data flow model: Static Single Assignment (-ish…)

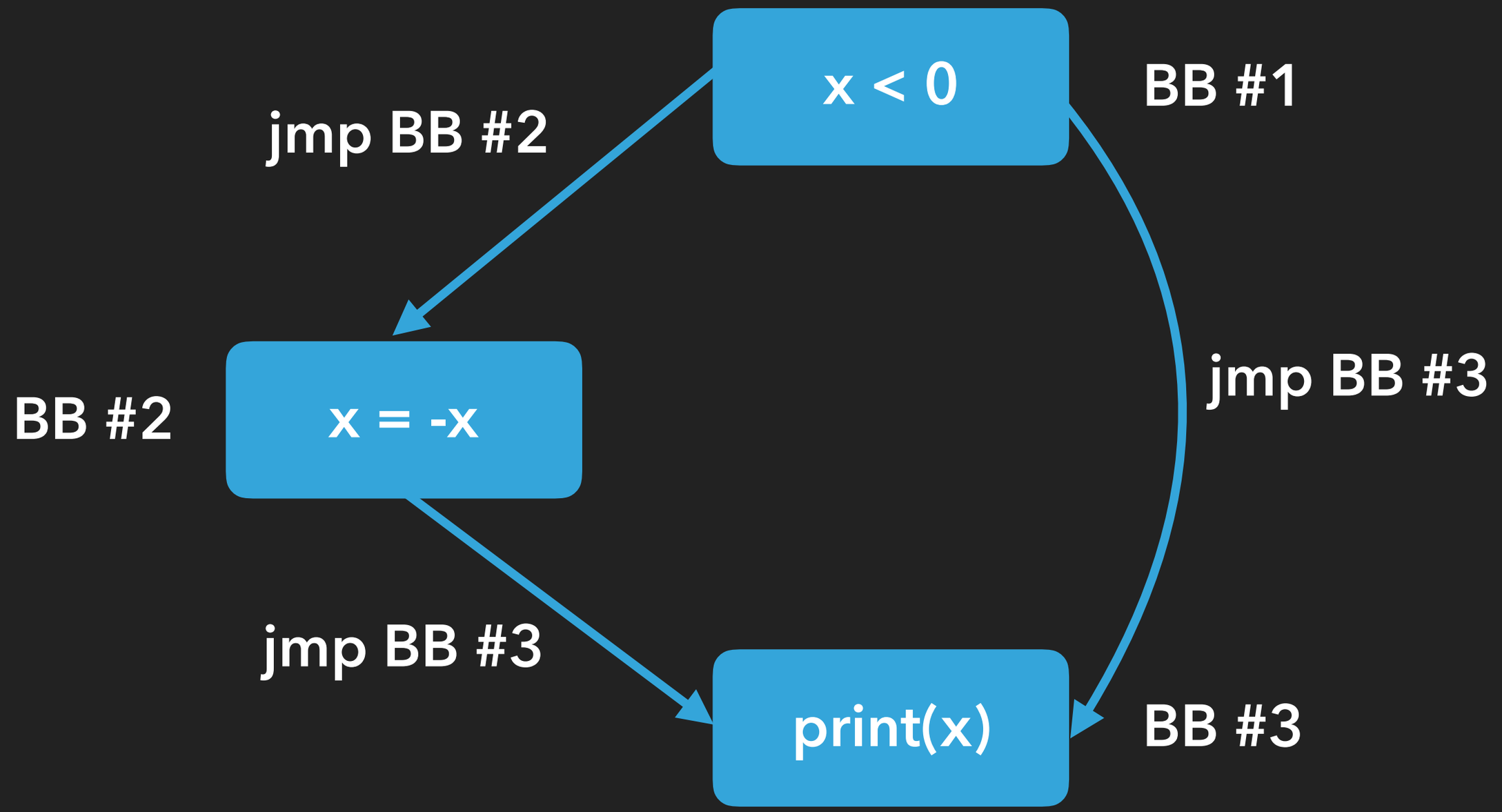
CONTROL FLOW GRAPH (CFG)

- Fundamental abstraction: Basic Blocks
  - Sequence of instructions without control flow inside
  - Jumps and returns must be at the end
  - Target of jump must be the first instruction
  - Function calls are still allowed inside BBs

CONTROL FLOW GRAPH (CFG)

- CFGs are Directed Cyclic Graphs
- Nodes: Basic Blocks
- Edges point from jump instructions to their targets

CONTROL FLOW GRAPH (CFG)



STATIC SINGLE ASSIGNMENT (SSA)

- No mutation: names are permanently bound to one value
- Assignment is represented using versioning
  - New version of variable is created by renaming (typically, by appending integer version numbers)
  - Mentions of original variable refer to the new version thereafter
- Assignment is definition; definition must precede uses

STATIC SINGLE ASSIGNMENT (SSA)

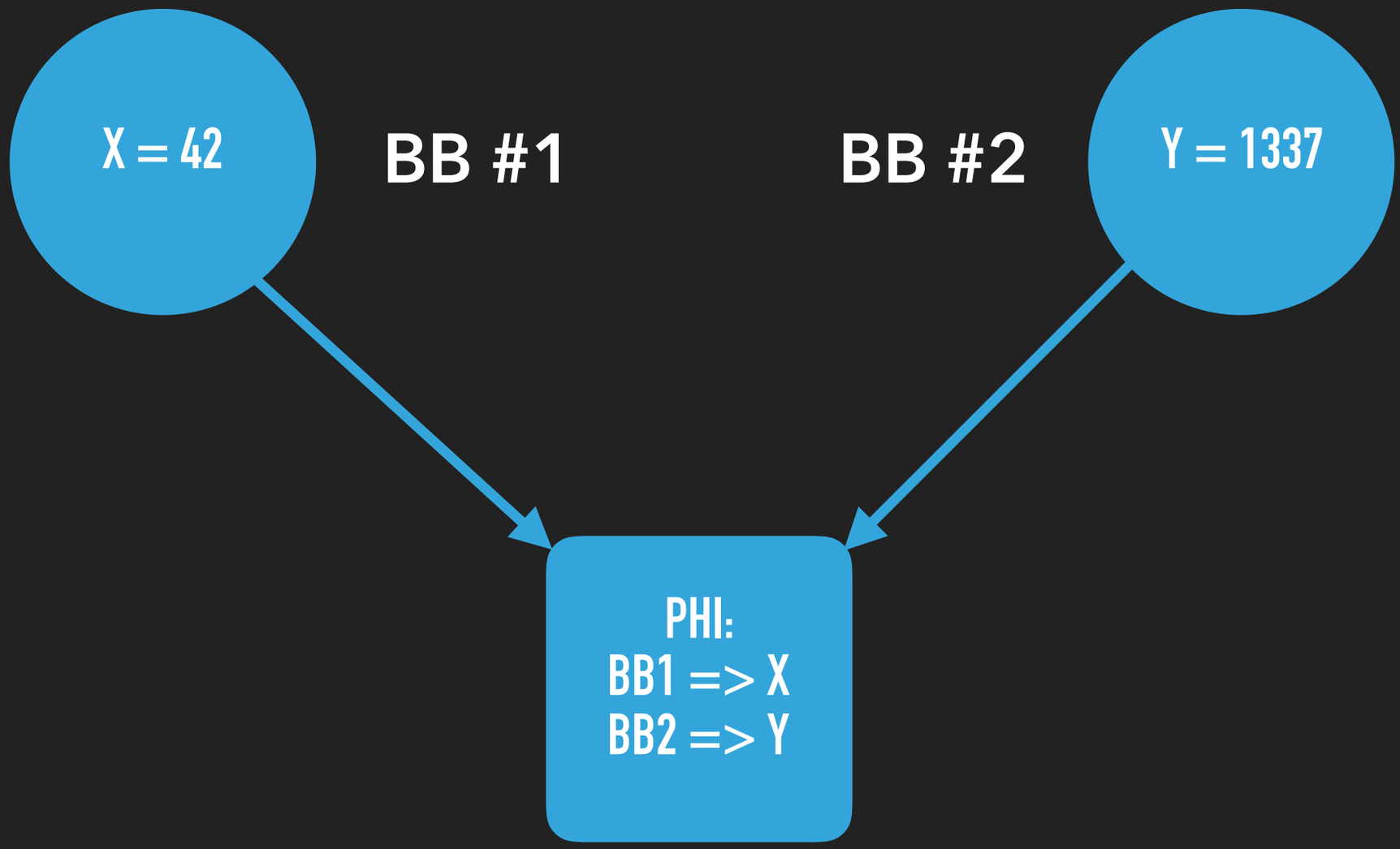
```
var x = 42
print(x)
x = x + 1
print(x)
x = x + 1
print(x)
```

```
x = 42
print(x)
x_1 = x + 1
print(x_1)
x_2 = x_1 + 1
print(x_2)
```

PHI NODES IN SSA

- Flow-sensitive value selection: PHI nodes
  - "Magic": output is one of the inputs, depending on where control flow comes from (incoming basic blocks)

PHI NODES IN SSA



LLVM BITCODE

- Our example: Print Absolute Value

```
void print_abs(int x) {
    if (x < 0) {
        x = -x;
    }
    print(x);
}
```

LLVM BITCODE

```
define void @print_abs(i32 %x) #0 {
    %1 = alloca i32, align 4
    store i32 %x, i32* %1, align 4
    %2 = load i32, i32* %1, align 4
    %3 = icmp slt i32 %2, 0
    br i1 %3, label %4, label %7

; <label>:4                                      ; preds = %0
    %5 = load i32, i32* %1, align 4
    %6 = sub nsw i32 0, %5
    store i32 %6, i32* %1, align 4
    br label %7

; <label>:7                                      ; preds = %4, %0
    %8 = load i32, i32* %1, align 4
    call void @print(i32 %8)
    ret void
}
```

LLVM BITCODE

- Compute Absolute Value

```
int abs(int x) {
    return x < 0 ? -x : x;
}
```

LLVM BITCODE

```
define i32 @abs(i32 %x) #0 {
    %1 = alloca i32, align 4
    store i32 %x, i32* %1, align 4
    %2 = load i32, i32* %1, align 4
    %3 = icmp slt i32 %2, 0
    br i1 %3, label %4, label %7

; <label>:4                                      ; preds = %0
    %5 = load i32, i32* %1, align 4
    %6 = sub nsw i32 0, %5
    br label %9

; <label>:7                                      ; preds = %0
    %8 = load i32, i32* %1, align 4
    br label %9

; <label>:9                                      ; preds = %7, %4
    %10 = phi i32 [ %6, %4 ], [ %8, %7 ]
    ret i32 %10
}
```

LLVM API ESSENTIALS

- Modules and Functions
- Values: Constants, Instructions
- Basic Blocks (are also Values)
- Builders: Convenience API for typical, basic usage
- Passes: Individual transform algorithms (e.g. optimizations)
- C++ API: cutting-edge, latest and greatest
- C API: Stable, can be bridged to Swift

LET'S GET TO WORK!