Compiler Design

Lecture 2:
General Structure of a Compiler

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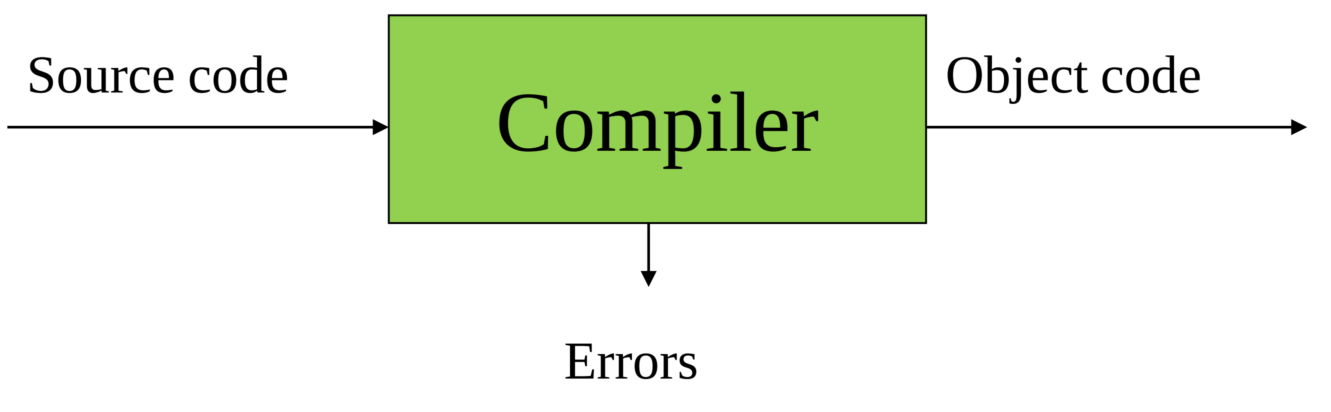
based on the slides of the course book

Overview of the Previous Lecture

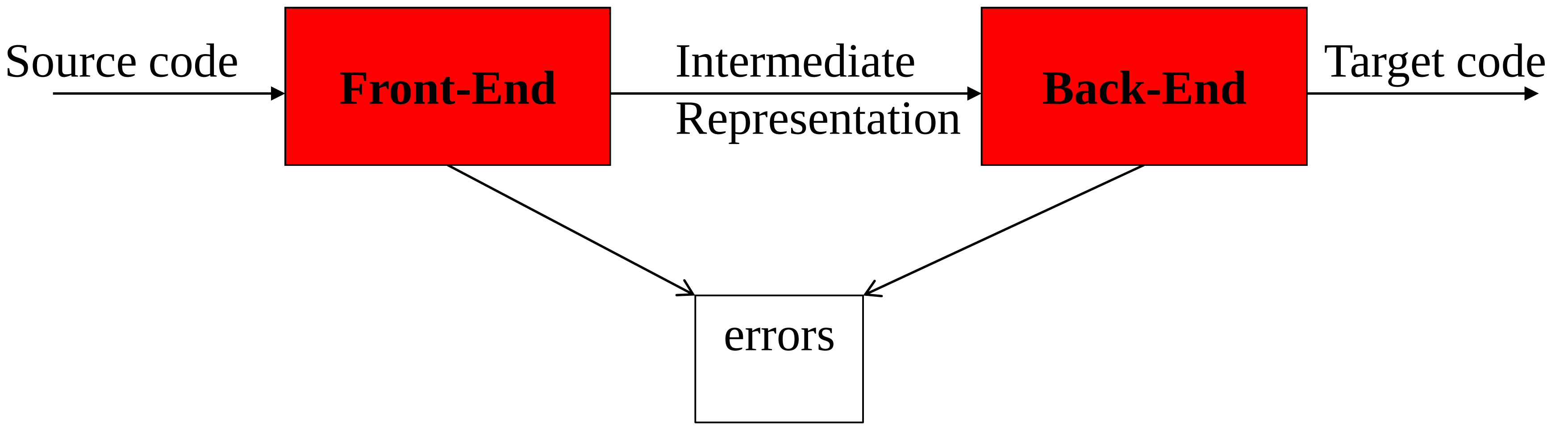
- The compiler tasks include
  - Generating correct code
  - Recognizing errors
  - Analyses and synthesises



Outline

- **Conceptual Structure**
- General Structure
- Overview of the Phases
- History

Conceptual Structure: Two Major Phases



- **Front-end** performs the **analysis** of the source language
- **Back-end** does the target language **synthesis**
- Typically front-end is **O(n),** while back-end is **NP-complete**

Front-end

- **Front-end** performs the **analysis** of the source language:
  - Recognises legal and illegal programs and reports errors
  - "Understands" the input program and collects its semantics in an IR
  - Produces IR and shapes the code for the back-end

Back-end

- **Back-end** does the target language **synthesis**:
  - Chooses instructions to implement each IR operation
  - Translates IR into target code
  - Needs to conform with system interfaces

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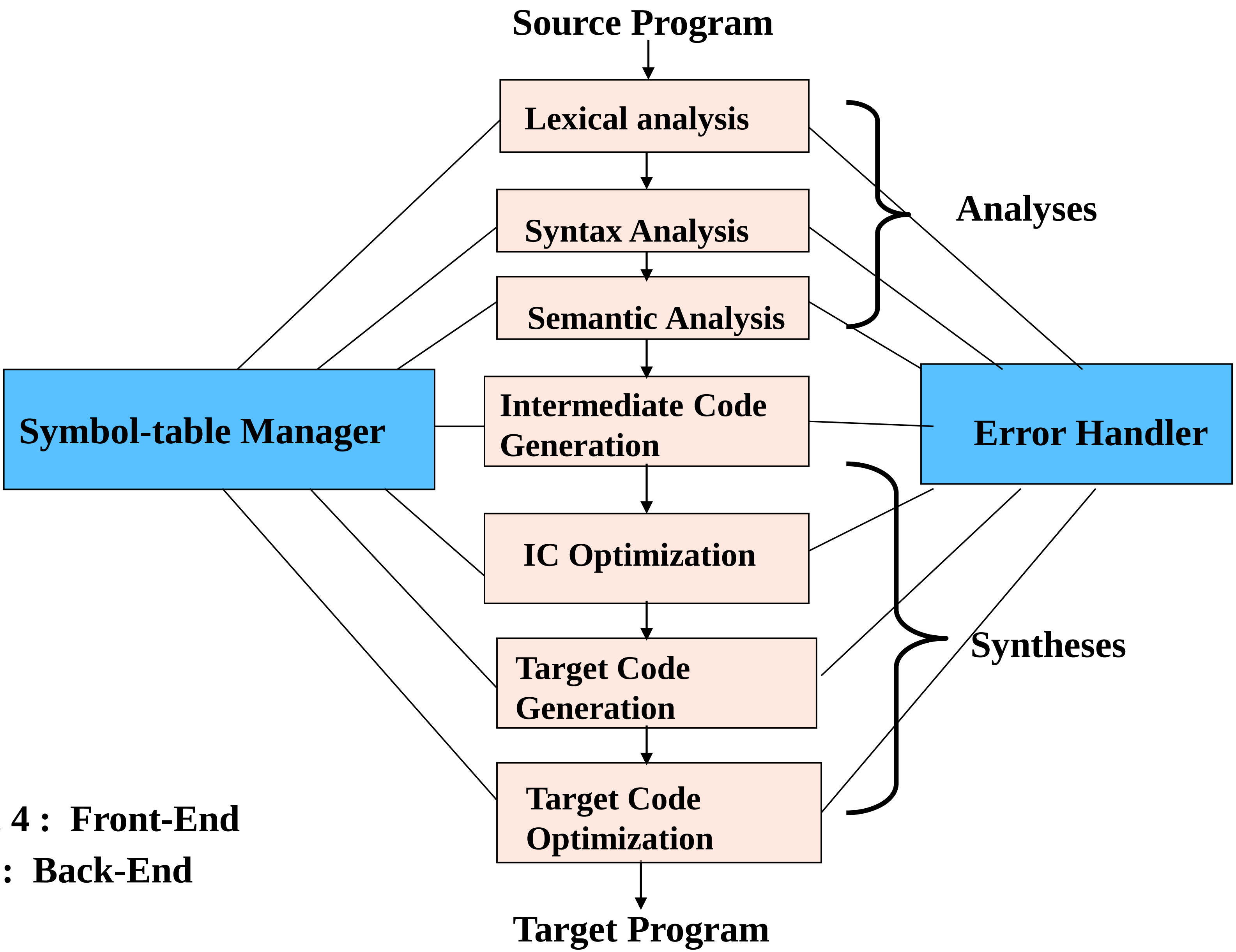
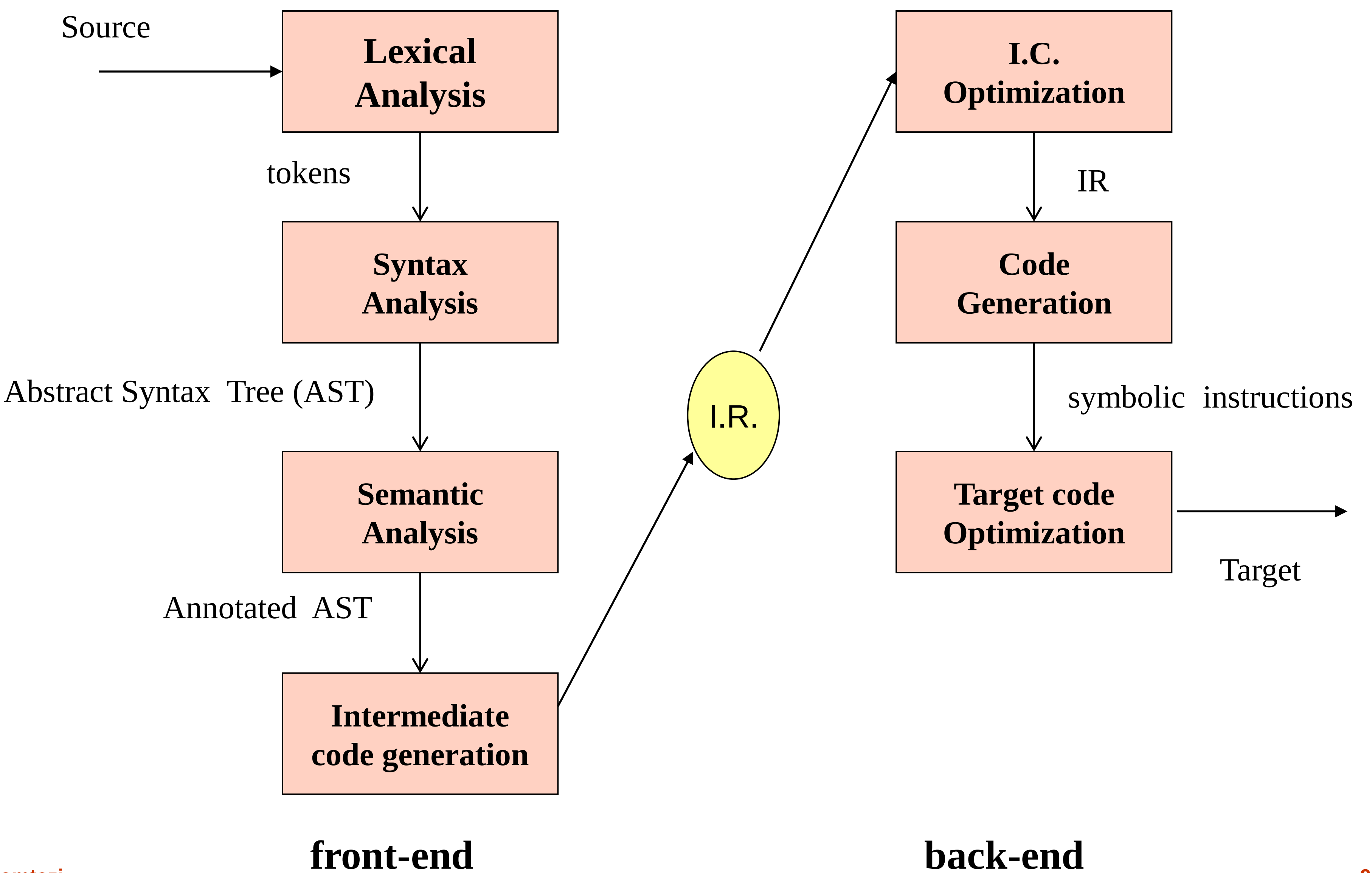
Compiler Components



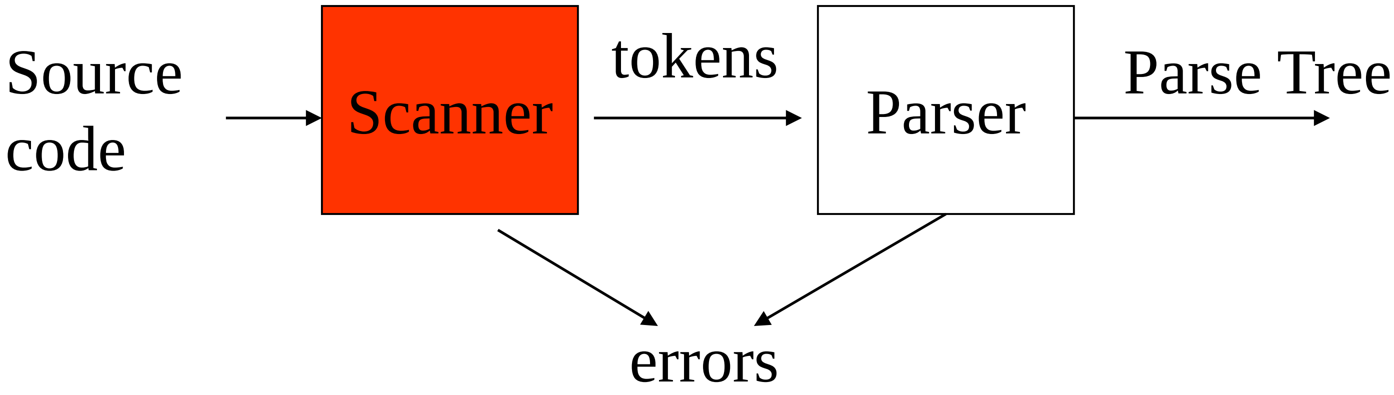
1, 2, 3, 4 : Front-End

5, 6, 7 : Back-End

Compiler Components



Front end



- Scanner:
  - Mapping characters into tokens – the basic unit of syntax

Lexical Analysis (Scanning)

- Reads characters in the source program and groups them into words (basic unit of syntax)

- Produces words and recognises what sort they are

- The output is called token and is a pair of the form

  <type, lexeme> or *<token_class, attribute>*

- Example:
  - `a=b+c` becomes <id,**a**> <=,> <id,**b**> <+,> <id,**c**>

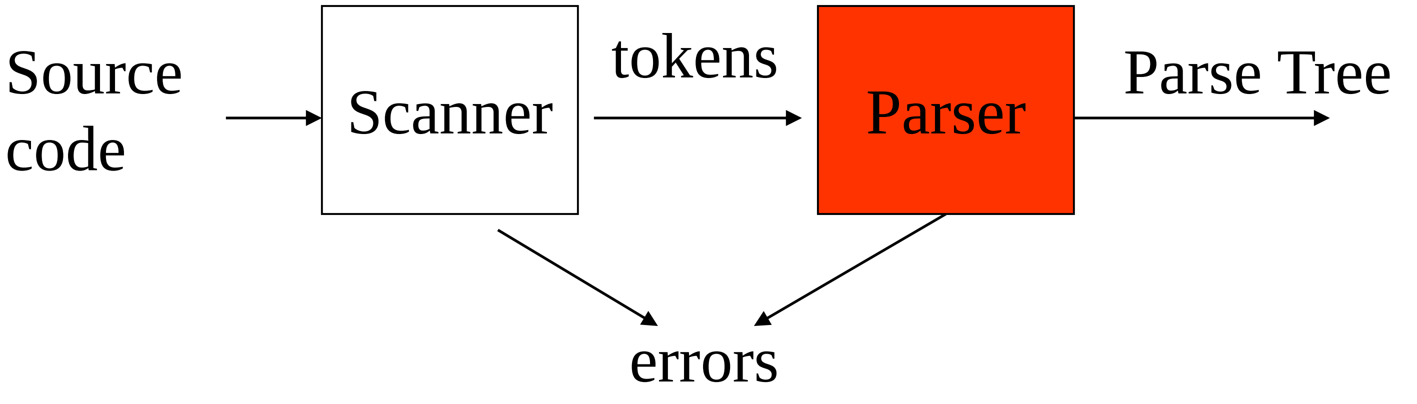
Lexical Analysis (Scanning)

- Needs to record each id attribute: keep a **symbol table**.
- Typical tokens: number, id, +, -, *, /, do, end
- Lexical analysis eliminates white space (tabs, blanks, comments)

Lexical Analysis (Scanning)

- A key issue is speed
  - Instead of using a tool like LEX it sometimes needed to write your own scanner
  - Use a specialised tool: e.g., flex
    - A tool for generating **scanners**: programs which recognise lexical patterns in text; for more info: `% man flex`

Front end



- Parser:
  - Recognize context-free syntax
  - Guide context-sensitive analysis
  - Construct IR
  - Produce meaningful error messages
  - Attempt error correction

Syntax Analysis (Parsing)

- Imposes a hierarchical structure on the token stream.
- This hierarchical structure is usually expressed by recursive rules.
- Context-free grammars formalize these recursive rules and guide syntax analysis.

Syntax Analysis

- Context free grammars are used to represent programming language syntaxes

- Example of a grammar to define simple algebraic expressions

<expr> ::= <expr> <op> <term> | <term>

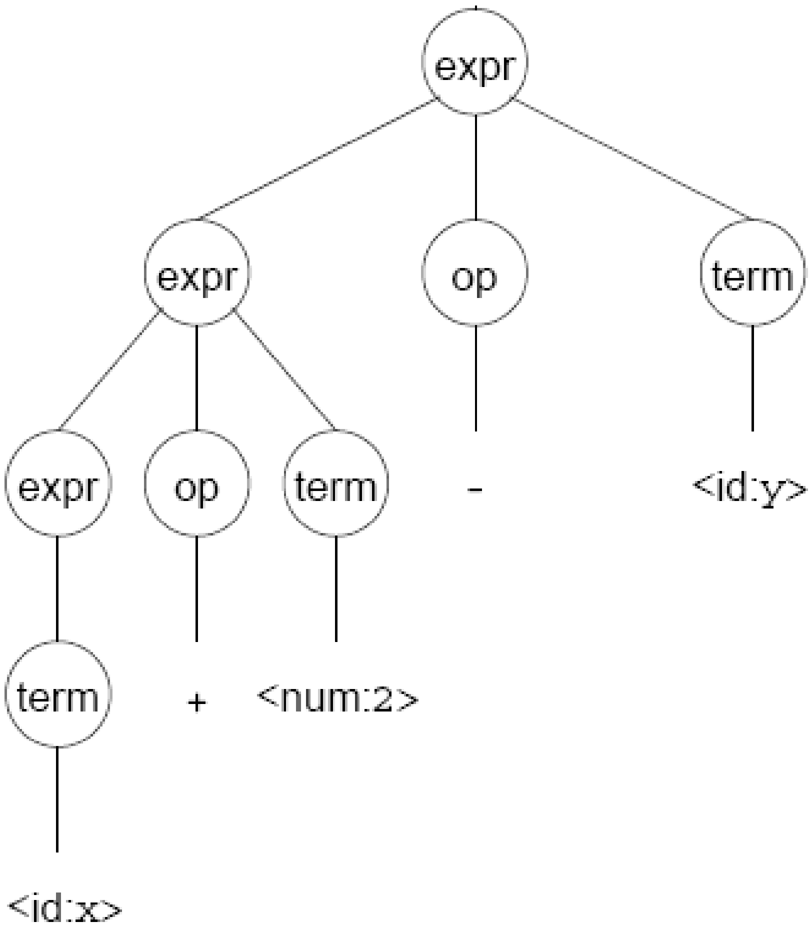
<term> ::= <number> | <id>

<op> ::= + | -

Syntax Analysis

- A parser tries to map a program to the syntactic elements defined in the grammar

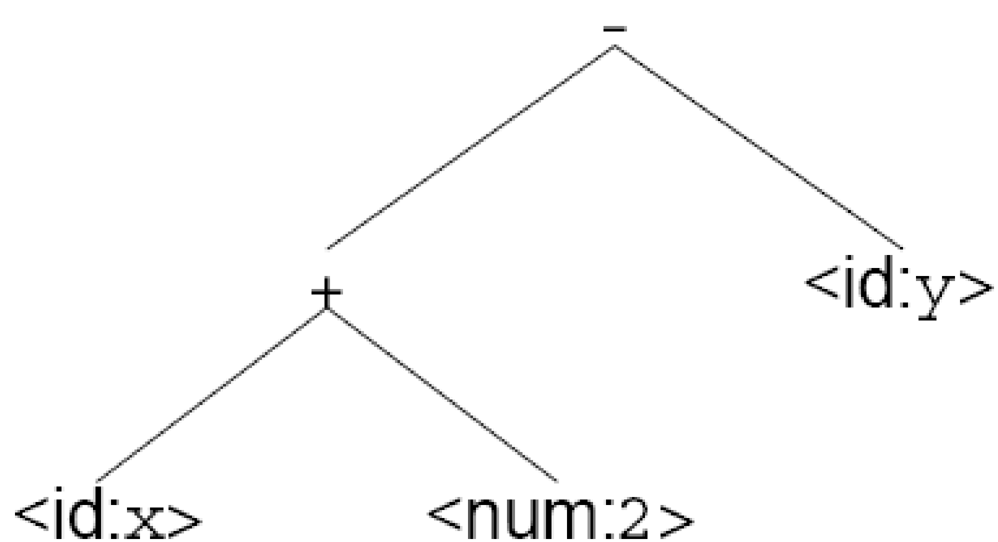
- A parse can be represented by a tree called a parse or syntax tree



Syntax Analysis

- A parse tree can be represented more compactly referred to as Abstract Syntax Tree (AST)

- AST can be used as IR between front end and back end



Syntax Analysis

- There are parser generators like YACC which automates much of the work

Parsing Example

- Grammar

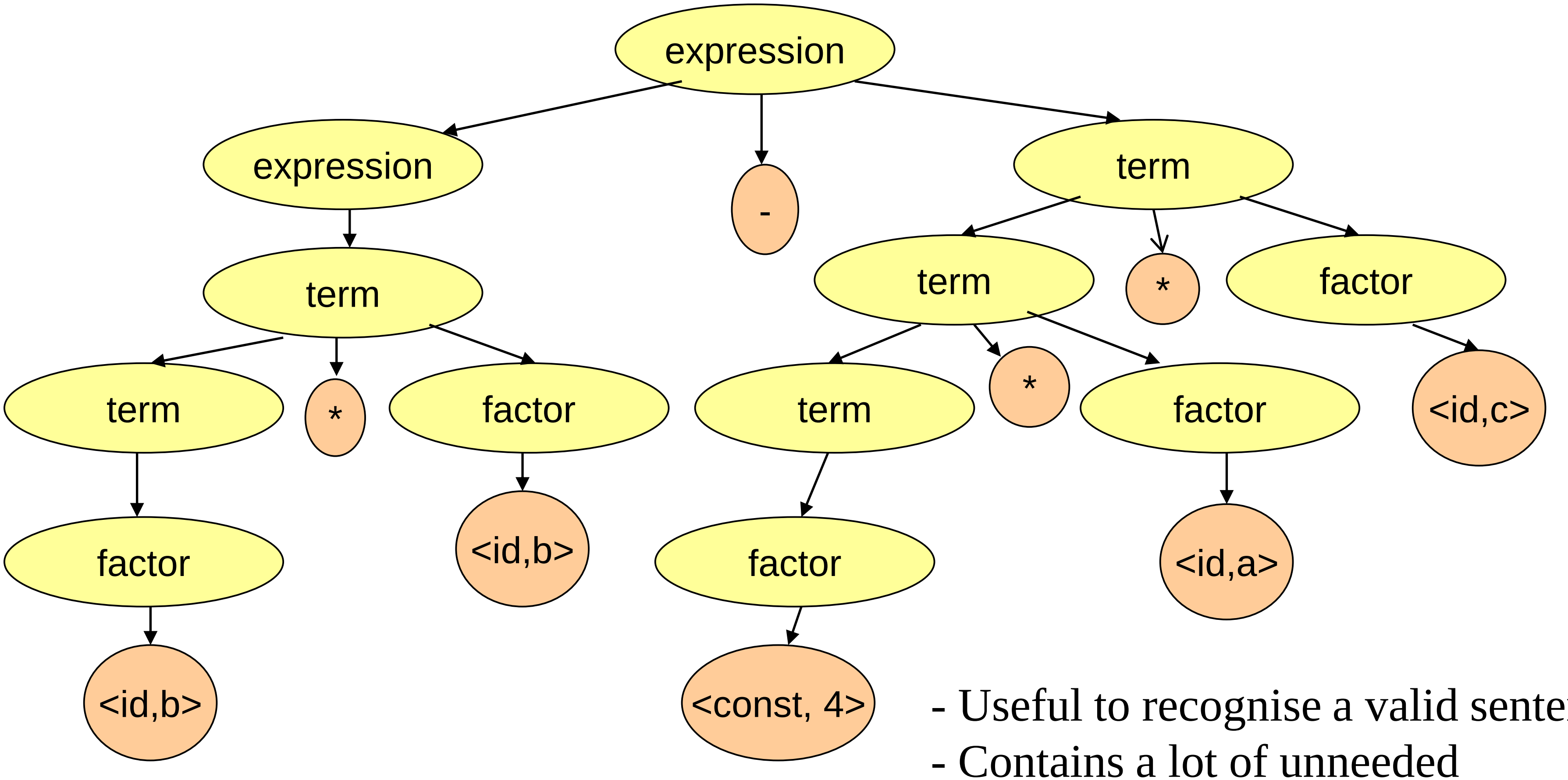
```
expression → expression '+' term | expression '-' term |
term
term → term '*' factor | term '/' factor | factor
factor → identifier | constant | '(' expression ')'
```

Parsing Example

- Parse tree for *b*b-4*a*c*

Parsing Example

- Parse tree for *b*b-4*a*c*



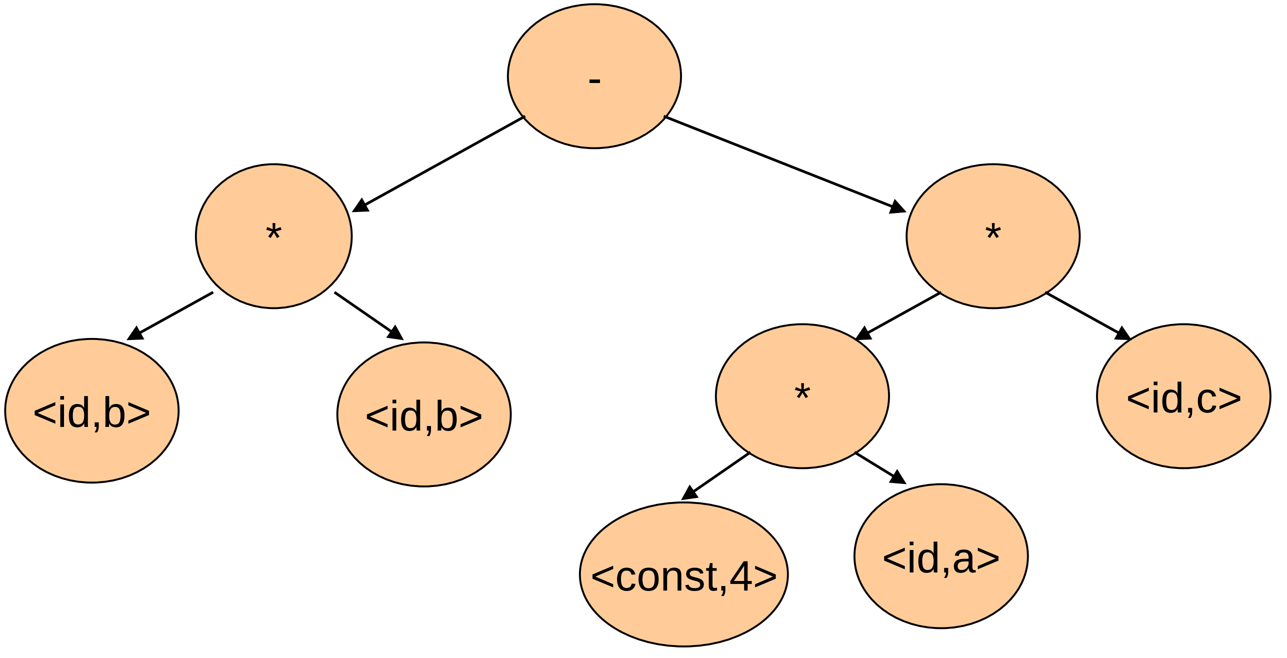
- Useful to recognise a valid sentence!
- Contains a lot of unneeded information!

Parsing Example

- AST for *b*b-4*a*c*

Parsing Example

- AST for *b*b-4*a*c*



An Abstract Syntax Tree (AST) is a more useful data structure for internal representation. It is a compressed version of the parse tree (summary of grammatical structure without details about its derivation)

Semantic Analysis (context handling)

- Collects context (semantic) information
- Checks for semantic errors
- Annotates nodes of the tree with the results

- Examples:
  - Type checking: report error if an operator is applied to an incompatible operand
  - Check flow-of-controls
  - Uniqueness or name-related checks

Intermediate code generation

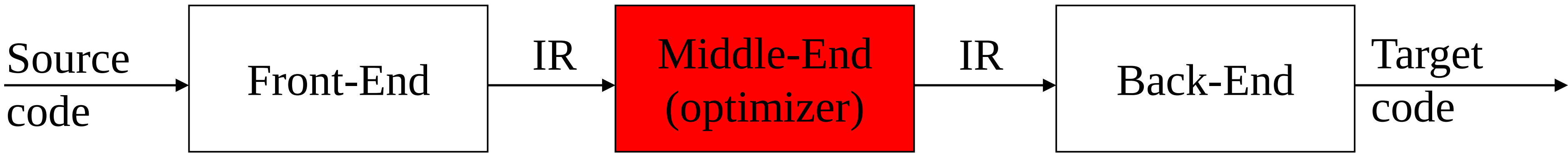
- Translate language-specific constructs in the AST into more general constructs
- A criterion for the level of “generality”:
  - It should be straightforward to generate the target code from the intermediate representation chosen.

Intermediate code generation

- Example of a form of IR for *b*b-4*a*c*

```
tmp1=4
tmp2=tmp1*a
tmp3=tmp2*c
tmp4=b*b
tmp5=tmp4-tmp3
```

Code Optimization



- IC Optimizer:
  - Improving the intermediate code
  - Improving the effectiveness of code generation and the performance of the target code

Code Optimization

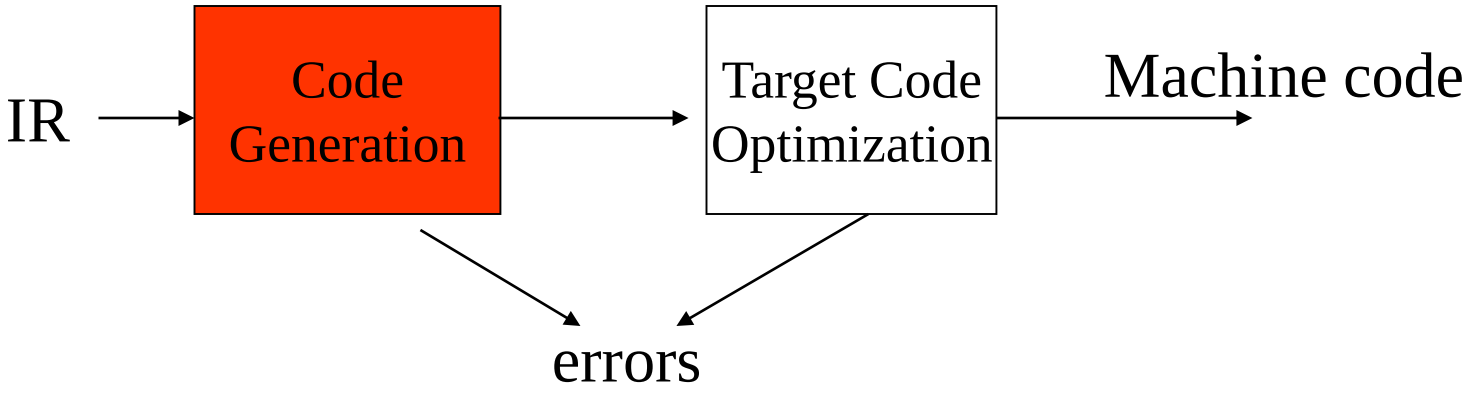
- Optimizations can range from trivial (e.g. constant folding) to highly sophisticated (e.g, in-lining).

- Example:

```
tmp1=4
tmp2=tmp1*a
tmp3=tmp2*c
tmp4=b*b
tmp5=tmp4-tmp3
```

```
tmp2=4*a
```

Back end

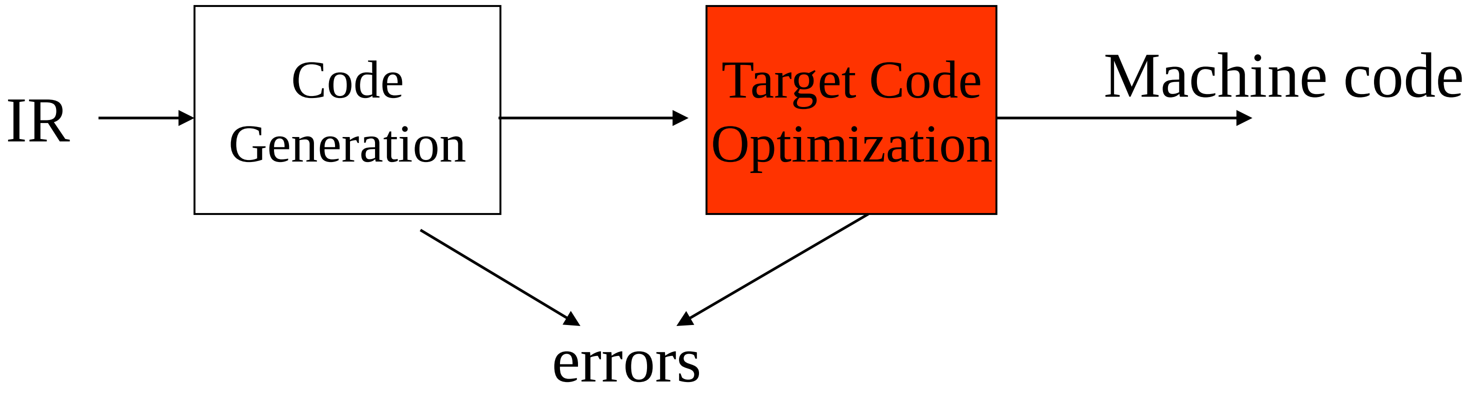


- Produce compact fast code
- Use available addressing modes

Code Generation Phase

- Map the AST into a linear list of target machine instructions in a symbolic form
  - Instruction selection
    - A pattern matching problem
  - Register allocation
    - Each value should be in a register when it is used
    - But there is only a limited number => NP-Complete problem
  - Instruction scheduling
    - Take advantage of multiple functional units: NP-Complete problem.

Back end



- Limited resources
- Optimal allocation is difficult

Target Code Optimization

- Target, machine-specific properties may be used to optimize the code

- Finally, machine code and associated information required by the Operating System are generated

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The Analysis Tasks For Compilation

- Three components:
  - **Lexical Analysis**:
    - Left-to-right scan to identify tokens
      - Token: sequence of chars having a collective meaning
  - **Syntax Analysis**:
    - Grouping of tokens into meaningful collection
  - **Semantic Analysis**:
    - Checking to ensure correctness of components

1. Lexical Analysis

- Easiest analysis - identify tokens which are the basic building blocks

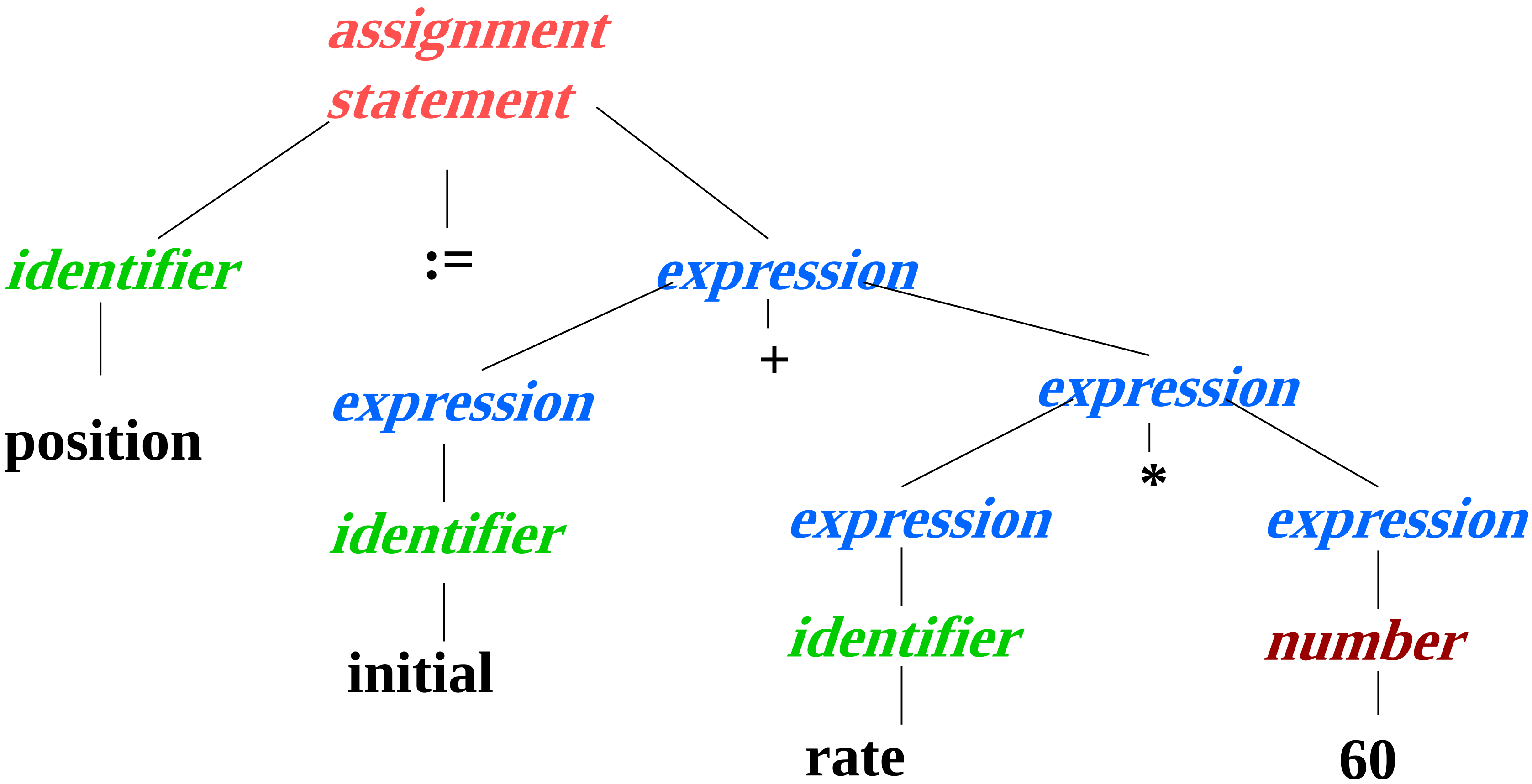
For Example:

Position := initial + rate * 60 ;

All are tokens

- Blanks, line breaks, etc. are scanned out

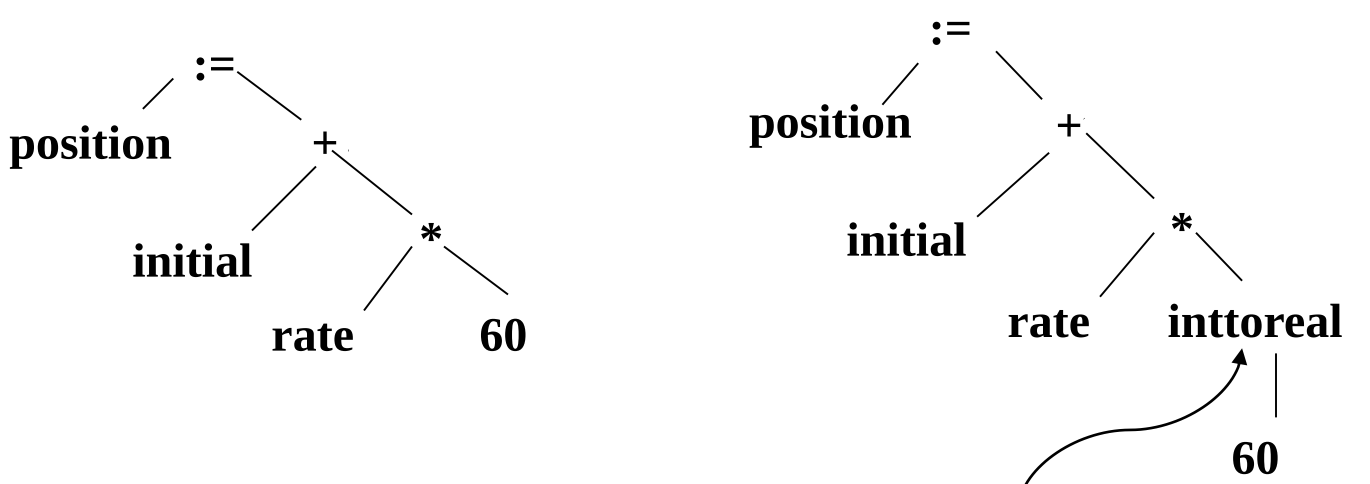
2. Syntax Analysis or Parsing



Nodes of tree are constructed using a grammar for the language

3. Semantic Analysis

- Finds Semantic Errors



Syntax Tree

Conversion Action

- One of the most important activity in this phase:
  - Type checking - legality of operands

Supporting Phases/ Activities for Analysis

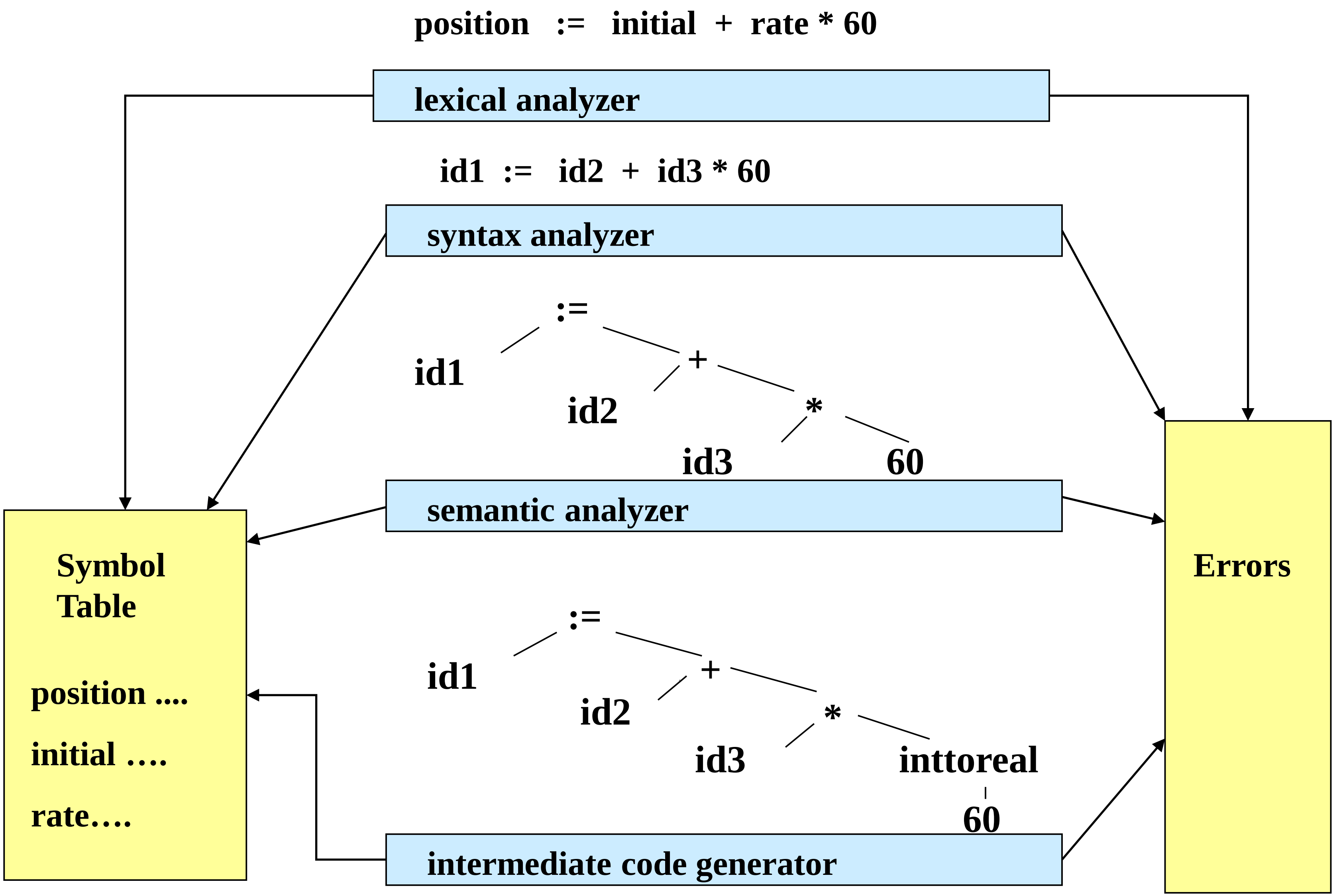
- Symbol table creation / maintenance
  - Contains info (storage, type, scope, args) on each "meaningful" token, typically identifiers
  - Data structure created / initialized during lexical analysis
  - Utilized / updated during later analysis & synthesis

- Error handling
  - Detection of different errors which correspond to all phases
  - What happens when an error is found?

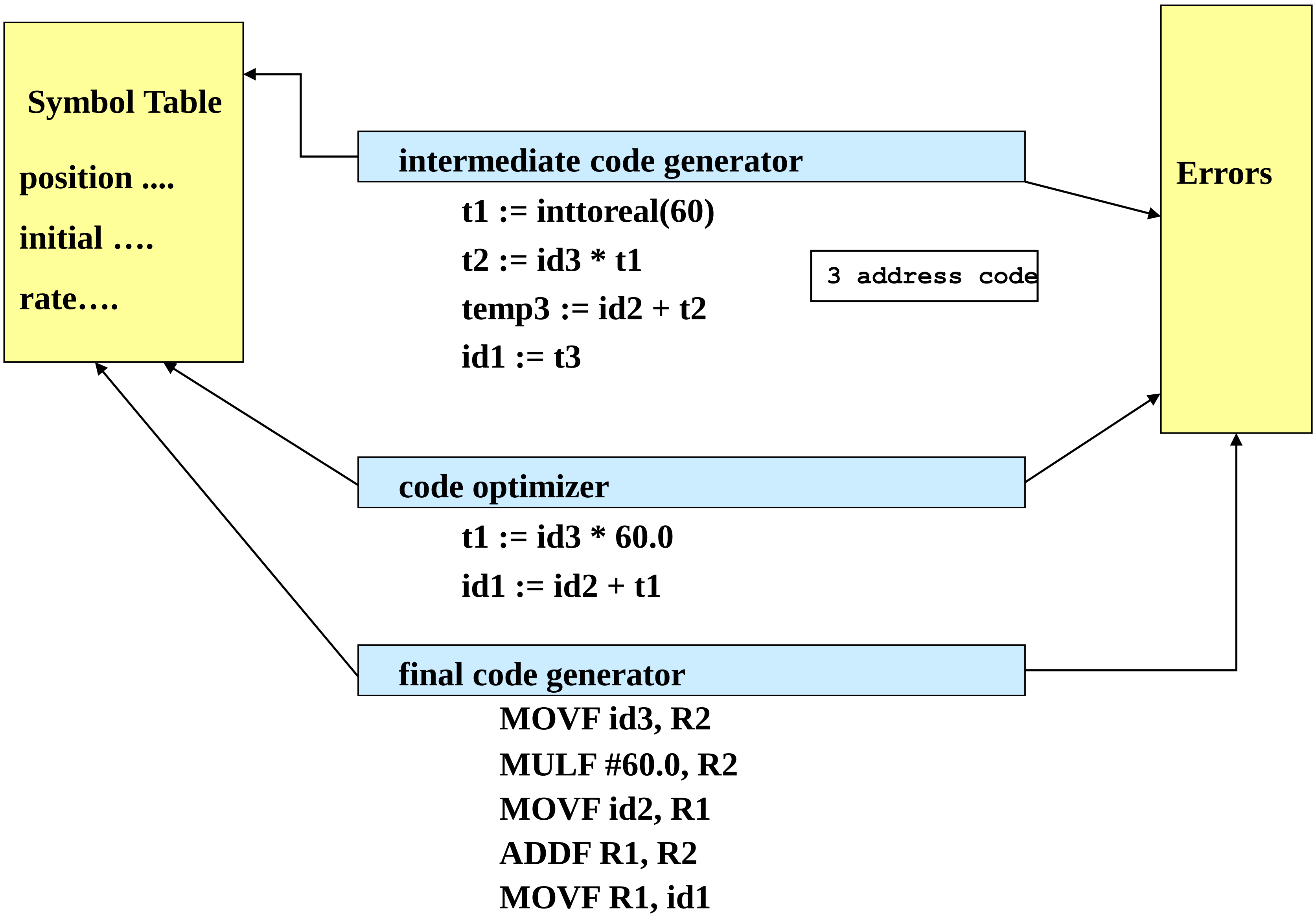
The Synthesis Tasks For Compilation

- Intermediate code generation
  - Abstract machine version of code - independent of architecture
  - Easy to produce and do final, machine dependent code generation
- Intermediate code optimization
  - Find more efficient ways to execute code
  - Replace code with more optimal statements
- Final code generation
  - Generate relocatable machine dependent code
- Code optimization
  - With a very limited view improves produced final code

Reviewing the Entire Process



Reviewing the Entire Process



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History

- Emphasis of compiler construction research
  - 1945-1960: code generation
    - Need to "prove" that high-level programming can produce efficient code ("automatic programming").
  - 1960-1975: parsing
    - Proliferation of programming languages
    - Study of formal languages reveals powerful techniques.
  - 1975-...: code generation and code optimization

Knuth (1962): "*in this field there has been an unusual amount of parallel discovery of the same technique by people working independently*"

History

- The Move to Higher-Level Programming Languages
  - Machine Languages (1st generation)
  - Assembly Languages (2nd generation) – early 1950s
  - High-Level Languages (3rd generation) – later 1950s
  - 4th generation higher level languages (SQL, Postscript)
  - 5th generation languages (logic based, eg, Prolog)
  - Other classifications:
    - Imperative (how); declarative (what)
    - Object-oriented languages
    - Scripting languages

Summary

- Parts of a compiler can be generated automatically using generators based on formalisms

- E.g.:
  - Scanner generators: flex
  - Parser generators: bison

- Next lecture: Introduction to lexical analysis.

Reading

- Aho2, Sections 1.2, 1.3
- Aho1, pp. 1-24;
- Grune [Chapter 1 up to Section 1.8]
- Cooper & Torczon (1st edition), Sections 1.4, 1.5

Question?