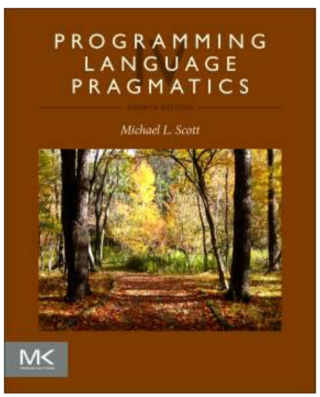
Syntax and Lexical Analysis

17-363/17-663: Programming Language Pragmatics



Reading: PLP chapter 2 through section 2.2

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Specifying Syntax

- Let's start by specifying the idea of a *digit*:

$$digit \longrightarrow \texttt{0} \mid \texttt{1} \mid \texttt{2} \mid \texttt{3} \mid \texttt{4} \mid \texttt{5} \mid \texttt{6} \mid \texttt{7} \mid \texttt{8} \mid \texttt{9}$$

- From this we can build *natural numbers*:

$$non\_zero\_digit \longrightarrow \texttt{1} \mid \texttt{2} \mid \texttt{3} \mid \texttt{4} \mid \texttt{5} \mid \texttt{6} \mid \texttt{7} \mid \texttt{8} \mid \texttt{9}$$
$$natural\_number \longrightarrow non\_zero\_digit\ \ digit\,^{*}$$

- Simple concepts like these can be expressed with *regular expressions*

Regular Expressions

- A regular expression is one of the following:
  - A character
  - The empty string, denoted by ε
  - Two regular expressions concatenated
  - Two regular expressions separated by | (i.e., or)
  - A regular expression followed by the Kleene star ***** (concatenation of zero or more strings)

Regular Expressions

- Numerical constants accepted by a simple hand-held calculator:

$$
\begin{aligned}
\textit{number} &\longrightarrow \textit{integer} \mid \textit{real} \\
\textit{integer} &\longrightarrow \textit{digit}\ \textit{digit}^* \\
\textit{real} &\longrightarrow \textit{integer}\ \textit{exponent} \mid \textit{decimal}\ (\,\textit{exponent} \mid \epsilon\,) \\
\textit{decimal} &\longrightarrow \textit{digit}^*\ (\ .\ \textit{digit} \mid \textit{digit}\ .\ )\ \textit{digit}^* \\
\textit{exponent} &\longrightarrow (\,\texttt{e} \mid \texttt{E}\,)\ (\,\texttt{+} \mid \texttt{-} \mid \epsilon\,)\ \textit{integer} \\
\textit{digit} &\longrightarrow \texttt{0} \mid \texttt{1} \mid \texttt{2} \mid \texttt{3} \mid \texttt{4} \mid \texttt{5} \mid \texttt{6} \mid \texttt{7} \mid \texttt{8} \mid \texttt{9}
\end{aligned}
$$

Practice with Regular Expressions

- Define a regular expression for C-style comments
  - You may use abbreviations like *non-** or *newline*
  - You may use Kleene + (1 or more) in addition to Kleene *

Practice with Regular Expressions

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- One solution (from the textbook)

$$comment \rightarrow /*\ (non\text{-}* \mid *\ non\text{-}/)^*\ *^+\ /$$
$$\mid\ //\ (non\text{-}newline)^*\ newline$$

From Tokens to Grammar

- Regular expressions are great for describing *tokens*
  - The smallest meaningful units of syntax – numbers, symbols, keywords, and identifiers
  - These constructs have no interesting recursive structure
- But real programs have recursive structure, even in expressions like 2 * (x + (y /3))
- To capture higher-level syntax we need *context-free grammars*

Context-Free Grammars

- A calculator expression grammar is recursive:

$$
\begin{aligned}
expr &\longrightarrow \texttt{id} \mid \texttt{number} \mid \texttt{-}\ expr \mid \texttt{(}\ expr\ \texttt{)} \\
&\quad \mid expr\ op\ expr \\
op &\longrightarrow \texttt{+} \mid \texttt{-} \mid \texttt{*} \mid \texttt{/}
\end{aligned}
$$

expr is defined in terms of itself!

Context-Free Grammars (CFGs)

- Anatomy of a CFG
  - In Backus-Naur Form (BNF)

A *symbol* is a terminal or a nonterminal

start symbol *S*

nonterminals *N*

expr ⟶ `id` | `number` | `-` *expr* | `(` *expr* `)`
 | *expr* *op* *expr*

op ⟶ `+` | `-` | `*` | `/`

terminals *T*

production

Context-Free Grammars

- In this grammar, generate the string **"slope * x + intercept"**

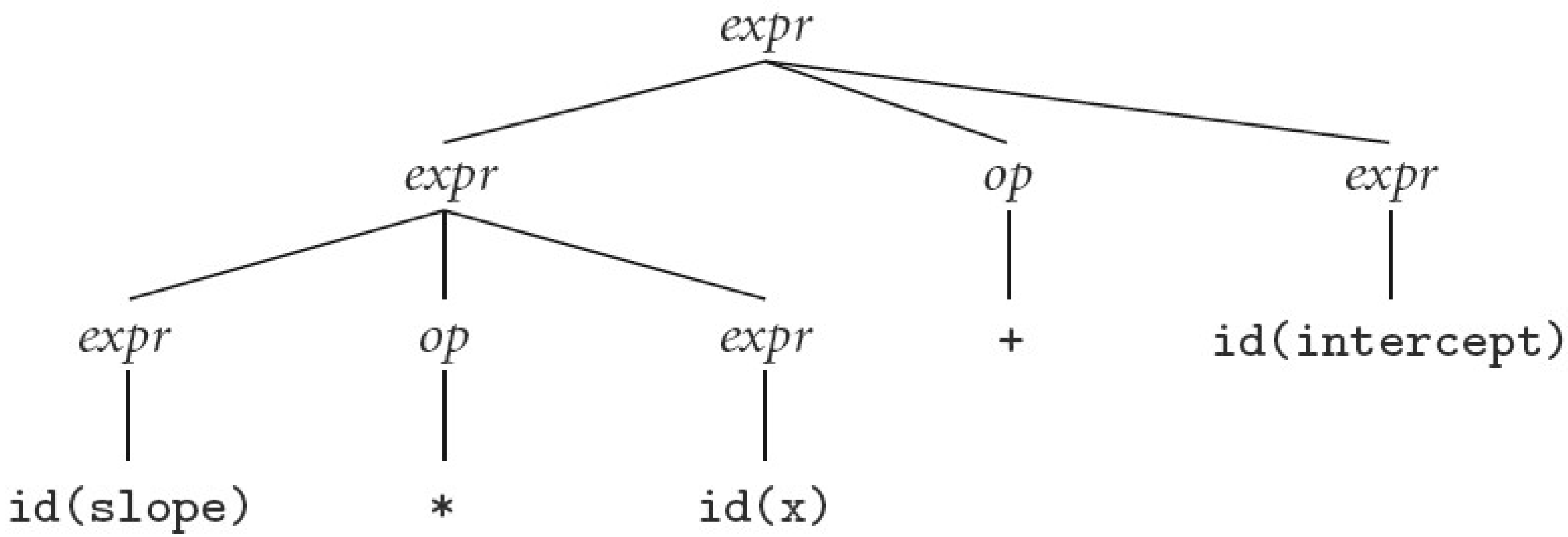
$$
\begin{aligned}
expr &\longrightarrow \texttt{id} \mid \texttt{number} \mid \texttt{-}\ expr \mid \texttt{(}\ expr\ \texttt{)} \\
&\quad \mid expr\ op\ expr \\
op &\longrightarrow \texttt{+} \mid \texttt{-} \mid \texttt{*} \mid \texttt{/}
\end{aligned}
$$

$$
\begin{aligned}
expr &\Longrightarrow expr\ op\ \underline{expr} \\
&\Longrightarrow expr\ \underline{op}\ \texttt{id} \\
&\Longrightarrow \underline{expr}\ \texttt{+ id} \\
&\Longrightarrow expr\ op\ \underline{expr}\ \texttt{+ id} \\
&\Longrightarrow expr\ \underline{op}\ \texttt{id + id} \\
&\Longrightarrow \underline{expr}\ \texttt{* id + id} \\
&\Longrightarrow \underset{\texttt{(slope)}}{\texttt{id}}\ \texttt{*}\ \underset{\texttt{(x)}}{\texttt{id}}\ \texttt{+}\ \underset{\texttt{(intercept)}}{\texttt{id}}
\end{aligned}
$$

This is called a *derivation*

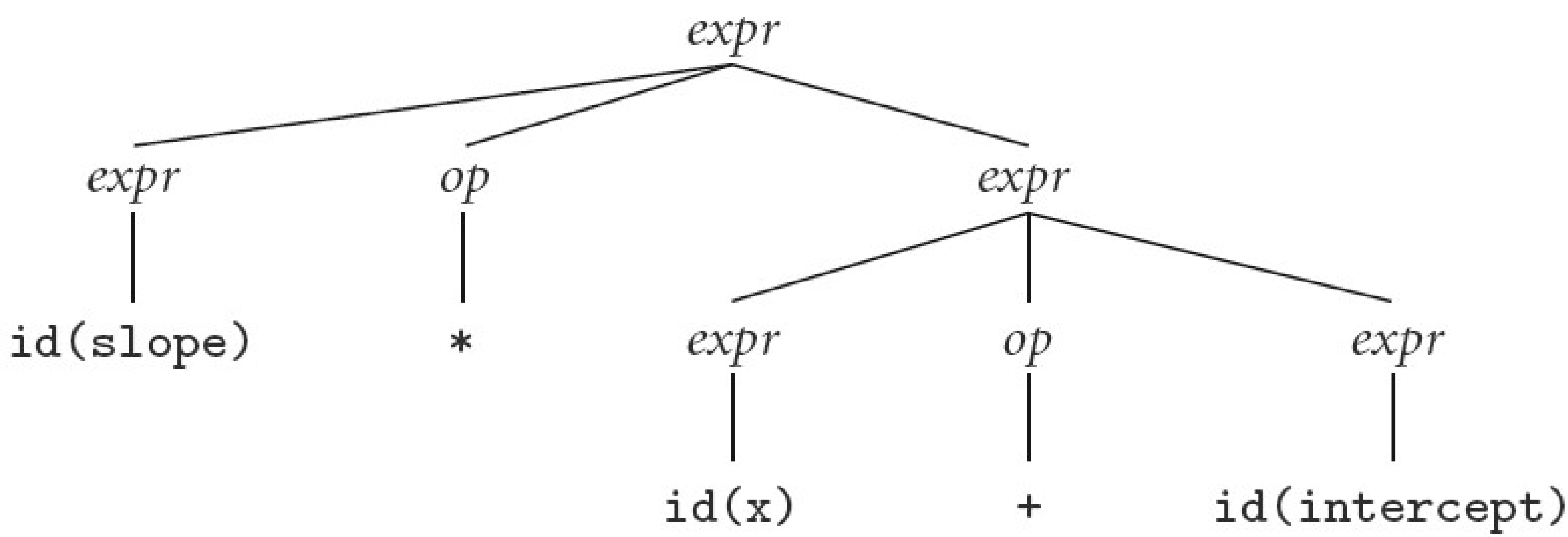
Context-Free Grammars

- Parse tree for expression grammar for **"slope * x + intercept"**



Context-Free Grammars

- Alternate (Incorrect) Parse tree for **"slope * x + intercept"**
- Our grammar is *ambiguous*



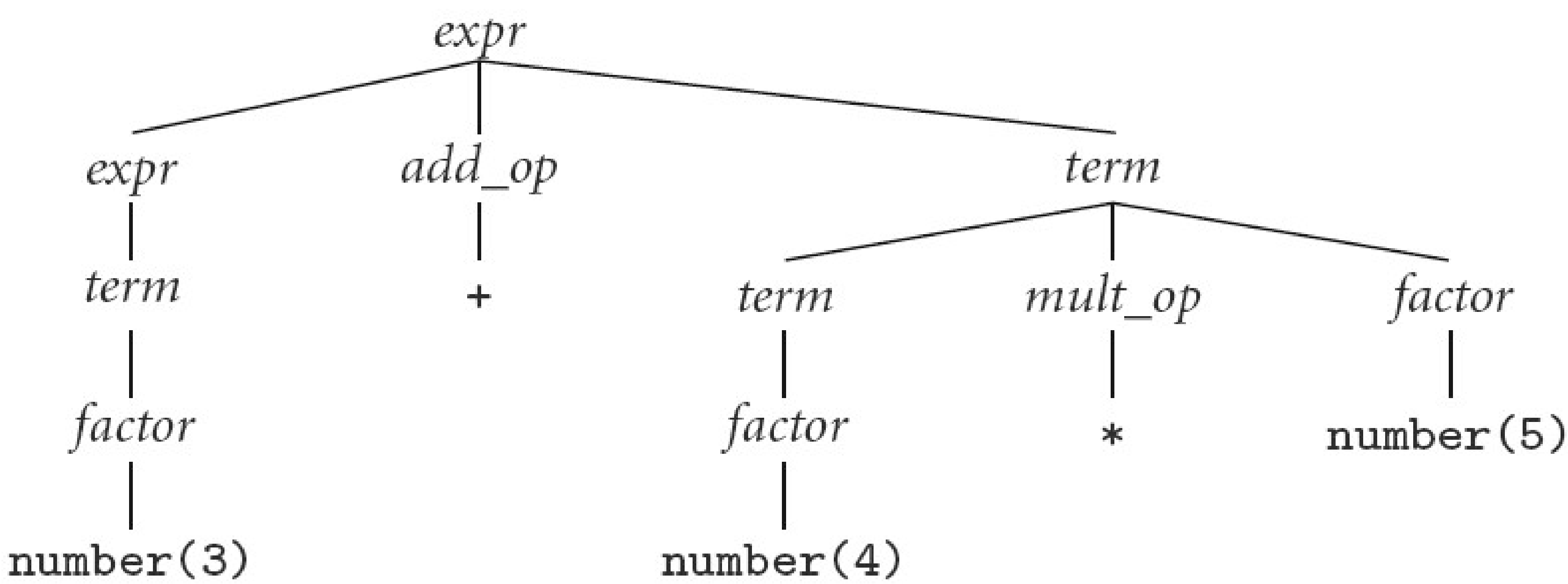
Context-Free Grammars

- A better version because it is unambiguous and captures precedence

1. *expr* ⟶ *term* | *expr add_op term*
2. *term* ⟶ *factor* | *term mult_op factor*
3. *factor* ⟶ `id` | `number` | `-` *factor* | `(` *expr* `)`
4. *add_op* ⟶ `+` | `-`
5. *mult_op* ⟶ `*` | `/`

Context-Free Grammars

- Parse tree for expression grammar (with left associativity) for **`3 + 4 * 5`**



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Practice with CFGs

- Add && and || to this grammar
  - Left-associative
  - Precedence: + over && over ||

1. *expr* ⟶ *term* | *expr add_op term*
2. *term* ⟶ *factor* | *term mult_op factor*
3. *factor* ⟶ `id` | `number` | `-` *factor* | `(` *expr* `)`
4. *add_op* ⟶ `+` | `-`
5. *mult_op* ⟶ `*` | `/`

Practice with CFGs

- One solution

orexpr → *andexpr* | *orexpr* || *andexpr*

andexpr → *expr* | *andexpr* && *expr*

1. *expr* ⟶ *term* | *expr add_op term*
2. *term* ⟶ *factor* | *term mult_op factor*
3. *factor* ⟶ `id` | `number` | `-` *factor* | `(` *expr* `)`
4. *add_op* ⟶ `+` | `-`
5. *mult_op* ⟶ `*` | `/`

Also replace with *orexpr*

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Lexical Analysis (or "Scanning")

- Divides source code into tokens
- Removes comments
- Saves text of identifiers, strings, numbers
- Tags tokens with line numbers, for error messages

```
y := x;
z := 1;
while y > 1 do
  z := z * y;
  y := y - 1
od
```

```
y := x ; z := 1 ; while y
> 1 do z := z * y ; y :=
y - 1 od
```

Scanning

- Suppose we are building an ad-hoc (hand-written) scanner for a calculator language:
  - We read the characters one at a time with look-ahead
- If it is one of the one-character tokens

  `(   )   +   -   *   /`

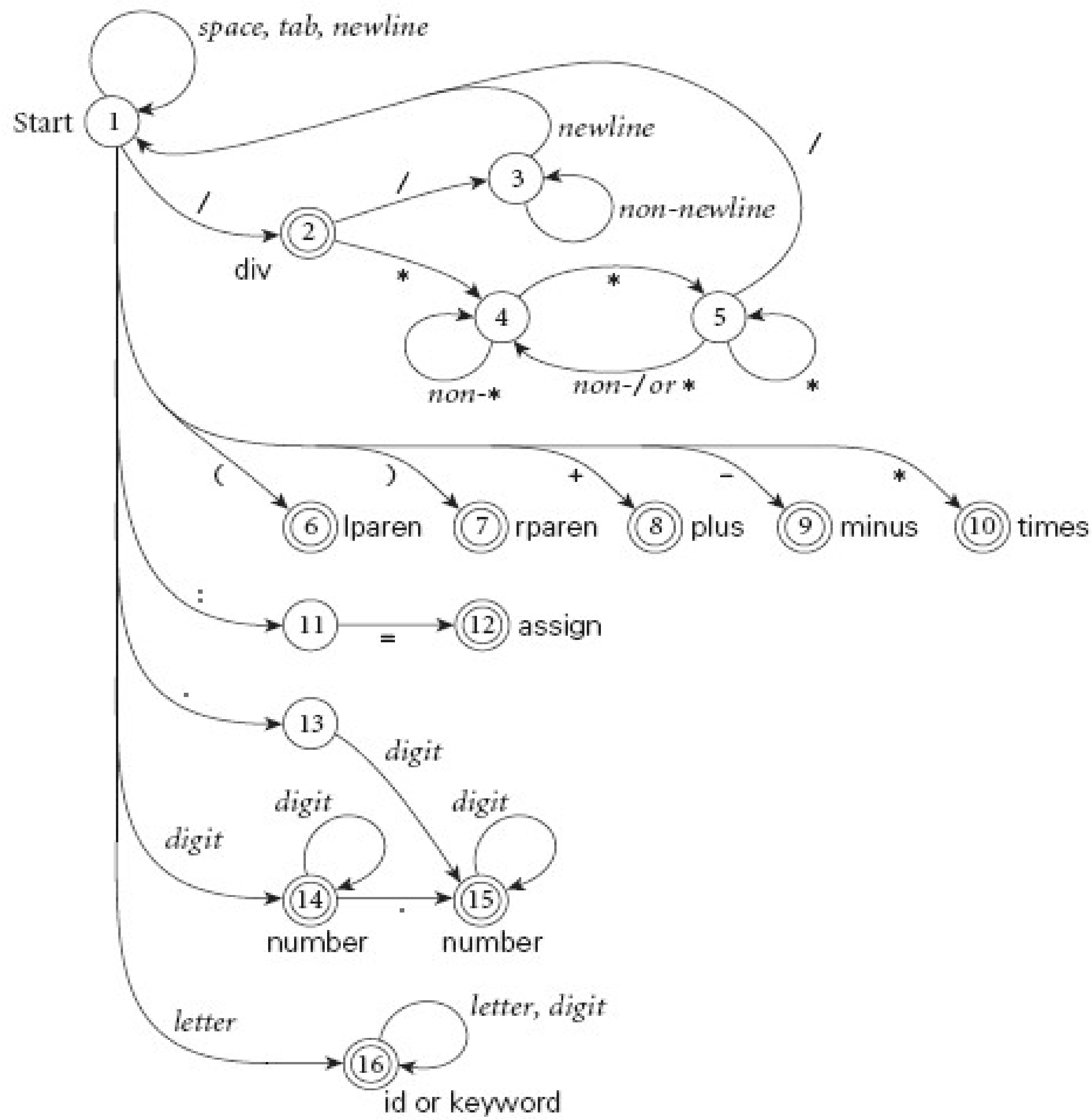
  we announce that token
- If it is a digit, we keep reading digits until we can’t anymore, then announce a number
- If it is a letter, we keep reading letters and digits and maybe underscores until we can't anymore, then announce an identifier

Scanning with floating point

- If it is a digit, we keep reading until we find a non-digit
  - if that is not a . we announce an integer
  - otherwise, we keep looking for a real number
  - if the character after the . is not a digit we announce an integer and reuse the . and the look-ahead

Scanning

- Pictorial representation of a scanner for calculator tokens, in the form of a finite automaton



Scanning

- This is a deterministic finite automaton (DFA)
  - Lex, scangen, etc. build these things automatically from a set of regular expressions
  - Specifically, they construct a machine that accepts the language
    `identifier | int const`
    `| real const | comment | symbol`
    `| ...`

Scanning

- We run the machine over and over to get one token after another
  - Nearly universal rule:
    - always take the longest possible token from the input thus foobar is foobar and never f or foo or foob
    - more to the point, `3.14159` is a real const and never `3`, `.`, and `14159`
- Regular expressions "generate" a regular language; DFAs "recognize" it

Scanning

- Scanners tend to be built three ways
  - ad-hoc
  - semi-mechanical pure DFA
    (usually realized as nested case statements)
  - table-driven DFA
- Ad-hoc generally yields the fastest, most compact code by doing lots of special-purpose things, though good automatically-generated scanners come very close

Scanning

- Writing a pure DFA as a set of nested case statements is a surprisingly useful programming technique
  - though it's often easier to use perl, awk, sed
  - for details see Example 2.16
- Table-driven DFA is what lex and scangen produce
  - lex/lalrpop in the form of C/Rust code
  - scangen in the form of numeric tables and a separate driver (for details see Figure 2.11-2.12)

Scanning

- Note that the rule about longest-possible tokens means you return only when the next character can't be used to continue the current token
  - the next character will generally need to be saved for the next token
- In some cases, you may need to peek at more than one character of look-ahead in order to know whether to proceed
  - In Pascal, for example, when you have a 3 and you a see a dot
    - do you proceed (in hopes of getting 3.14)?
      or
    - do you stop (in fear of getting 3..5)?

Scanning

- In messier cases, you may not be able to get by with any fixed amount of look-ahead. In Fortran, for example, we have

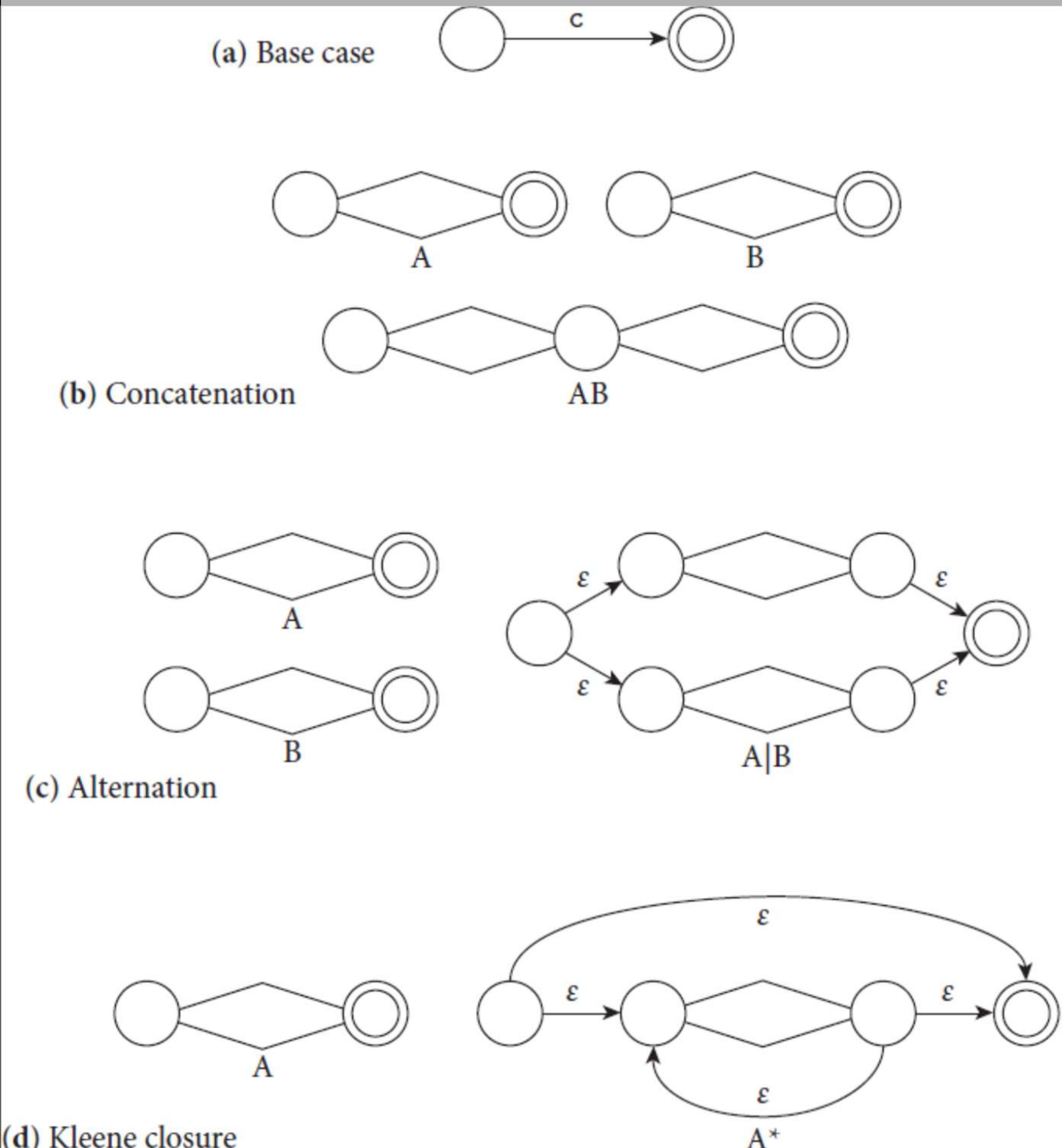
```
DO 5 I = 1,25  loop
DO 5 I = 1.25  assignment
               (to DO5I)
```

- Here, we need to remember we were in a potentially final state, and save enough information that we can back up to it, if we get stuck later

Converting a RE to a DFA

1. Write regular expressions for each construct
   – Except keywords – special case of identifiers
2. Construct NFA from REs
3. Convert NFA to a DFA (set of subsets)
4. Minimize DFA (find equivalence classes)
5. Fix up the result
   – Longest-possible token rule
   – Discard whitespace and comments
   – Distinguish keywords from identifiers
   – Save text, token location
   – Return a special EOF token at end of file

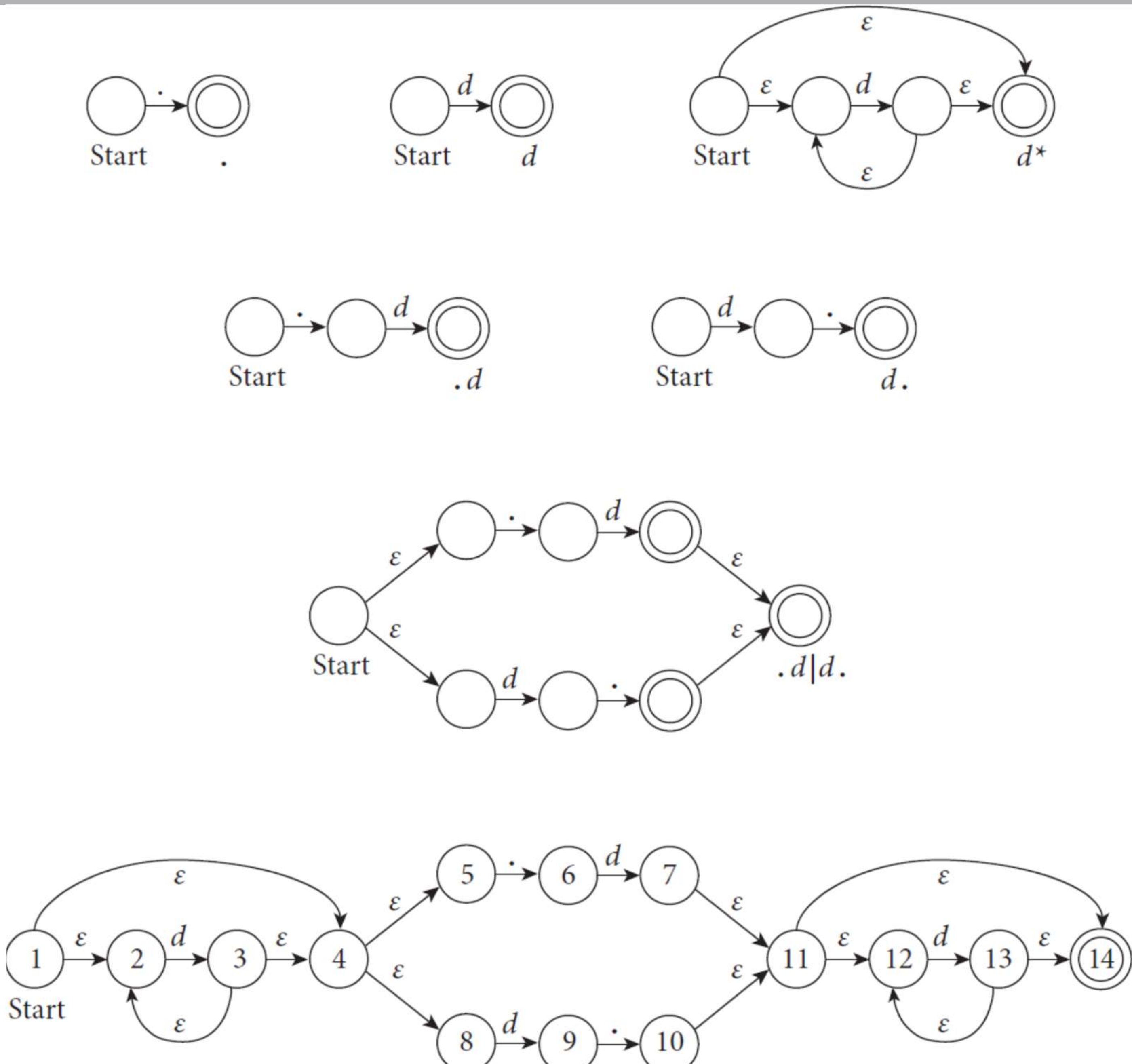
RE to NFA Construction



Let's apply this to

d* (. d | d .) d*

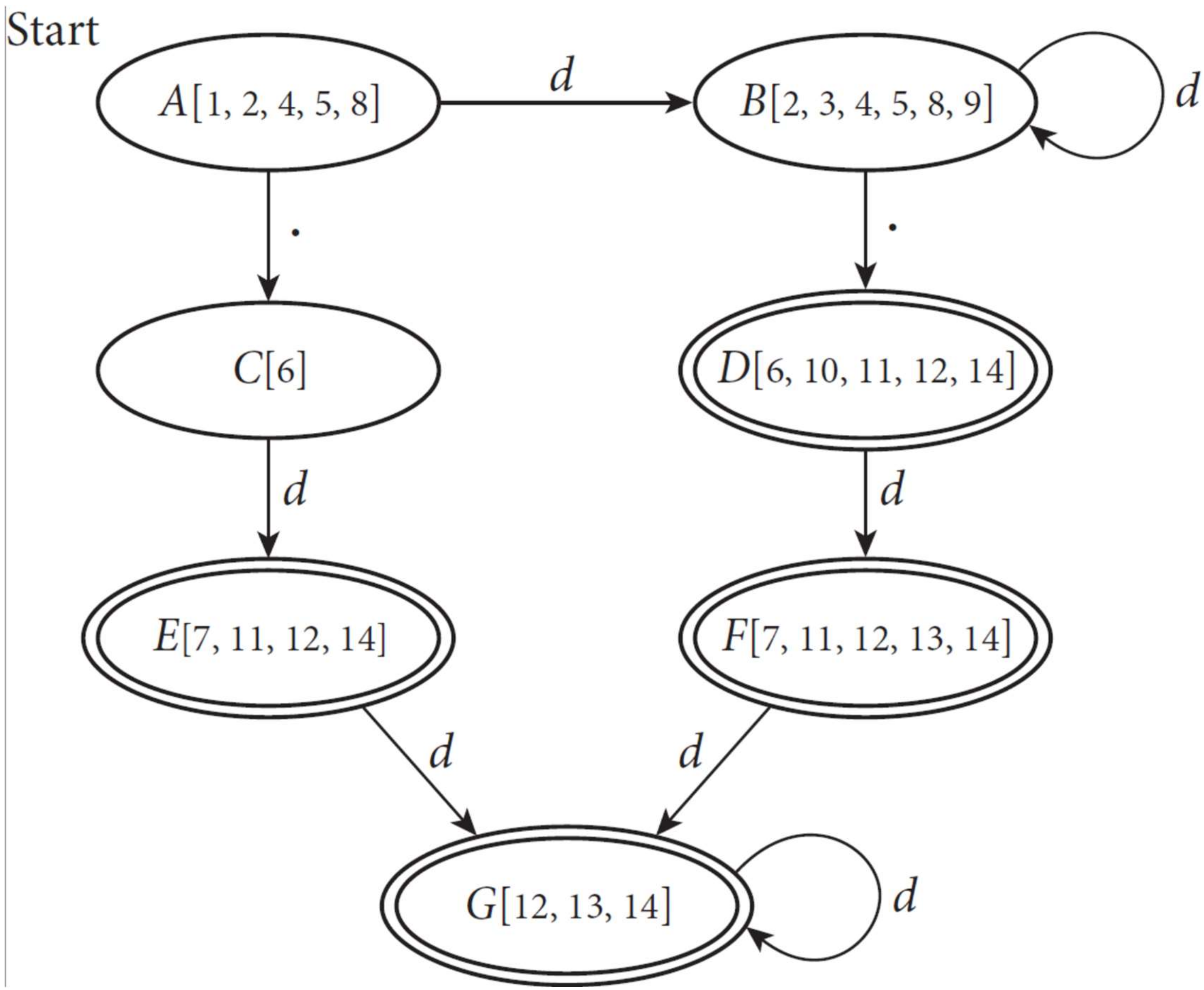
RE to NFA Construction



NFA to DFA Construction

- Each state in the DFA is a set of NFA states
  - "Set of subsets"
- The start DFA state contains the start NFA state, plus all states reachable through ϵ-transitions
- For each input that can be consumed from one of those NFA states, we create another DFA state with the set of destination states (plus states from ϵ-transitions)

NFA to DFA Construction (example)



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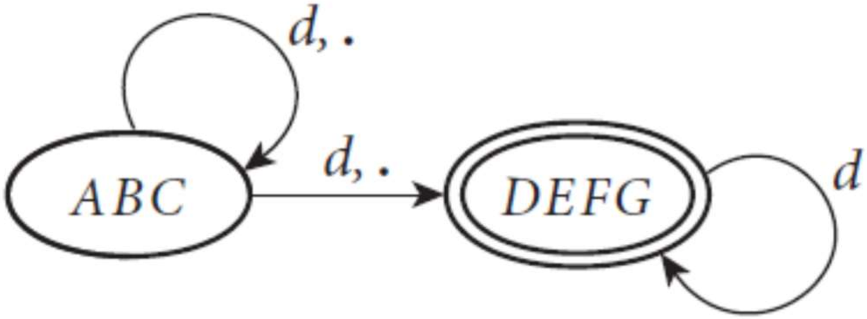
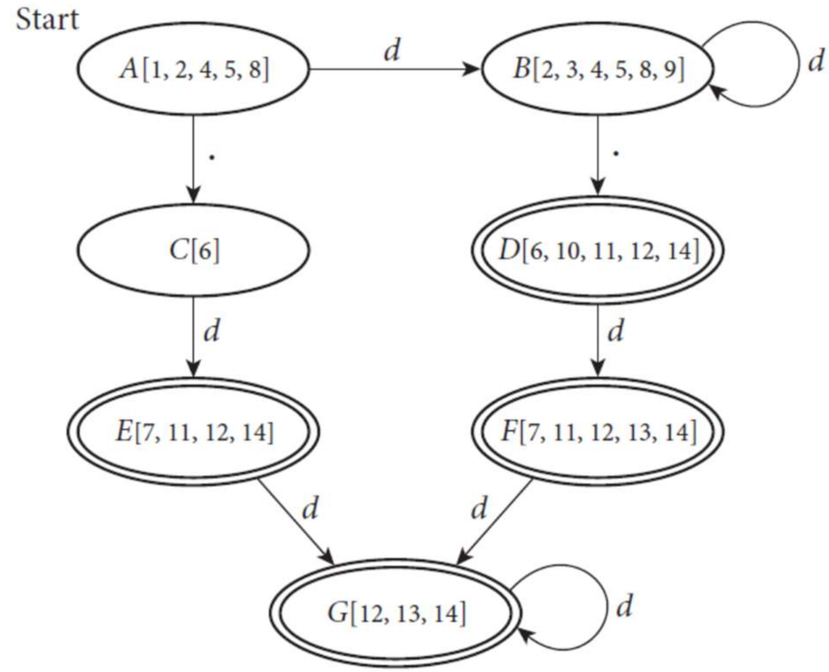
DFA Minimization

- Start by merging all DFA states into two equivalence classes: final and non-final
- Iteratively split the equivalence classes as follows:
  - Identify a class X with a nondeterministic transitions on some character c that lead to k other equivalence classes
  - Split X into k equivalence classes according to the destinations of these transitions

DFA Minimization

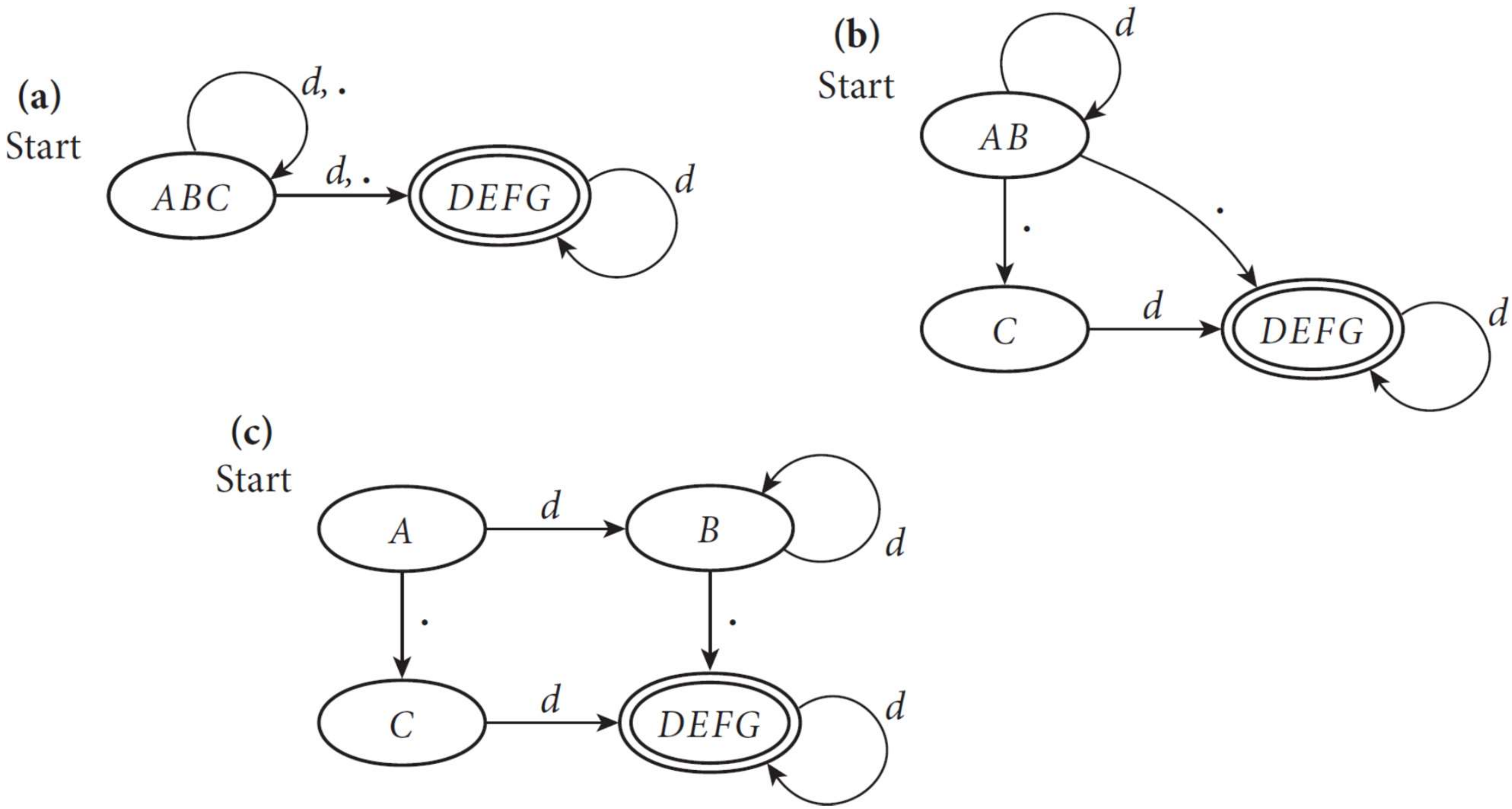




- Example: Consider the diagram on the left, derived by merging states from the one on the upper right.
- The transition from *ABC* on *d* is nondeterministic
- So we split *ABC* into two parts:
  - *AB* (where *d* transitions back to *ABC*)
  - *C* (where *d* transitions to *DEFG*)
- The result is (b) on the next page

DFA Minimization (example)

- From state (b) we can now make the . transition deterministic by splitting AB into A and B. Now we have a DFA.



Syntax and Lexical Analysis

- We use regular expressions to define tokens
  - Concatenation, alternation, repetition
- A scanner uses a DFA to recognize tokens
  - Often the DFA is machine-generated
- Context-free grammars define higher-level structure
  - Must structure the right way to avoid ambiguity
  - Interesting parsing challenges – future lecture!