Compilation Principle
编 译 原 理

第4讲：词法分析(4)

张献伟

xianweiz.github.io

DCS290, 3/12/2024

Welcome[欢迎加入]

- 21级计科/1班（李文军）
- 21级计科/2班（冯剑琳 + 林瀚）
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- 21级计科/2班（冯剑琳 + 林瀚）
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- 21级计科/系统+AI等+ （赵帅）

Time/Location[课时安排]

- **编译原理**（3学分，54学时）
  - 排课：1-18周
    - 周二：1-9周
    - 周四：1-18周
  - 每次授课包括2个课时
    - 第五节：14:20 - 15:05，第六节：15:15 - 16:00
  - 地点：教学大楼 ~~C104~~B205

- **编译器构造实验**（1学分，36学时）
  - 排课：1-18周
    - 周四：1-18周
  - 每次实验包括2个课时
    - 第七节：16:30 - 17:15，第八节：17:25 - 18:10
  - 地点：实验中心 B202

Slides/Office Hours[课件及答疑]

- 课件
  - 英文为主，术语中文标注
    - 课后或课前上传
  - 主页： https://arcsysu.github.io/teach/dcs290/s2024.html

xianweiz.github.io

> Teaching

- **Undergraduate**
  - § DCS290 - Compilation Principle, [2024s, 2023s, 2022s, 2021s].
  - § DCS3013 - Computer Architecture, [2022f].
- **Graduate**
  - § DCS5637/6207 - Advanced Computer Architecture, [2023f, 2022f, 2021f].

- 作业及实验提交
  - 超算习堂： https://easyhpc.net/course/164
- **课程QQ群： 189 205 980**
  - 通知提醒、答疑讨论

sysu–编译(张)

群号: 189205980

扫一扫二维码，加入群聊

QQ

- 线下答疑
  - 理论课前课间，或实验课期间
    - 其他时间需预约
  - Email: zhangxw79@mail.sysu.edu.cn

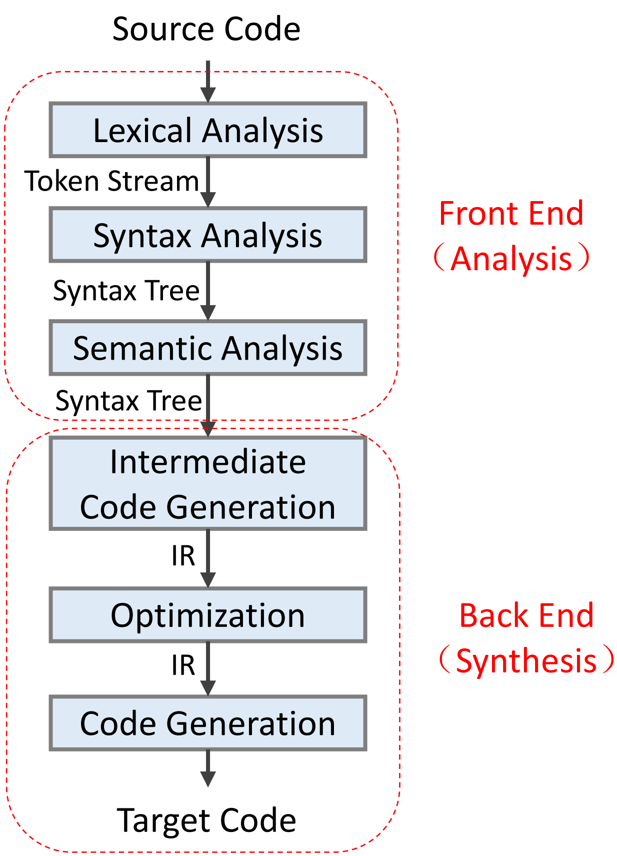
Grading[考核标准]

- **编译原理**
  - 课堂参与（15%）- 点名、提问、测试
  - 课程作业（25%）- 5次左右，理论
  - 期末考试（60%）- 闭卷
- **编译器构造实验**
  - 课堂参与（10%）- 签到、练习等
  - Project 1（20%）- Lexical Analysis
  - Project 2（20%）- Syntax/Semantic Analysis
  - Project 3（20%）- IR Generation
  - Project 4（30%）- Code Optimization

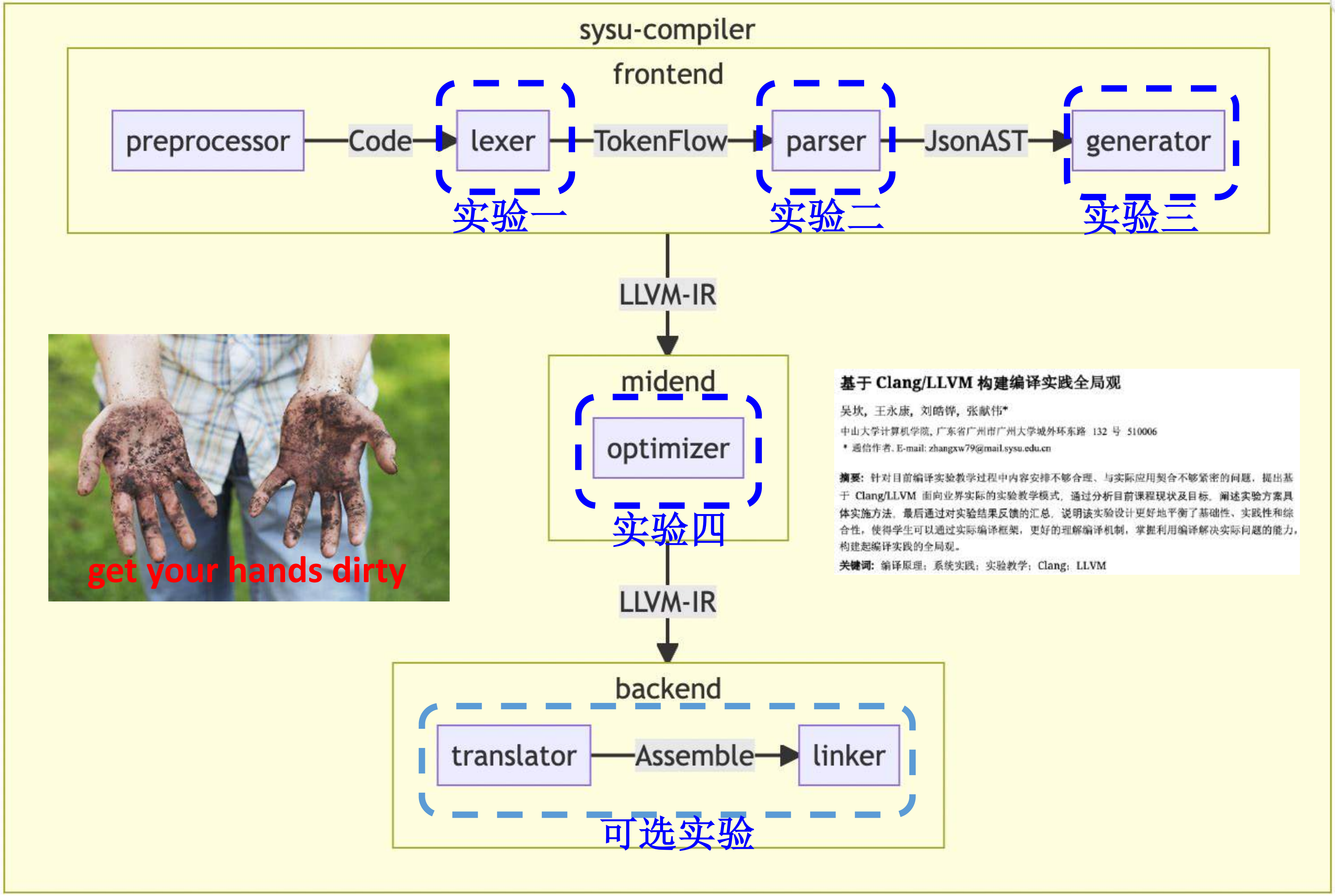
- 理论
  - 随机点名
    - 缺席优先
  - 随机提问
    - 后排优先
  - 随机测试
    - 不定时间
- 实验
  - 个人完成
    - 杜绝抄袭
  - 按时提交
    - 硬性截止
  - 侧重代码实现
    - 简略报告

Schedule-Lec[理论安排]

- **Lexical**: source code → tokens
  - RE, NFA, DFA, …
- **Syntax**: tokens → AST or parse tree
  - CFG, LL(1), LALR(1), …
- **Semantic**: AST → AST + symbol table
  - SDD, SDT, typing, scoping, …
- **Int. Code Generation**: AST → IR
  - TAC, offset, CodeGen, …
- **Optimization**: IR → (optimized) IR
  - BB, CFG, DAG, …
- **Code Generation**: IR → Instructions
  - Instruction, register, stack, …



Schedule-Lab[实验安排]



基于 Clang/LLVM 构建编译实践全局观

吴坎，王永康，刘皓铧，张献伟*
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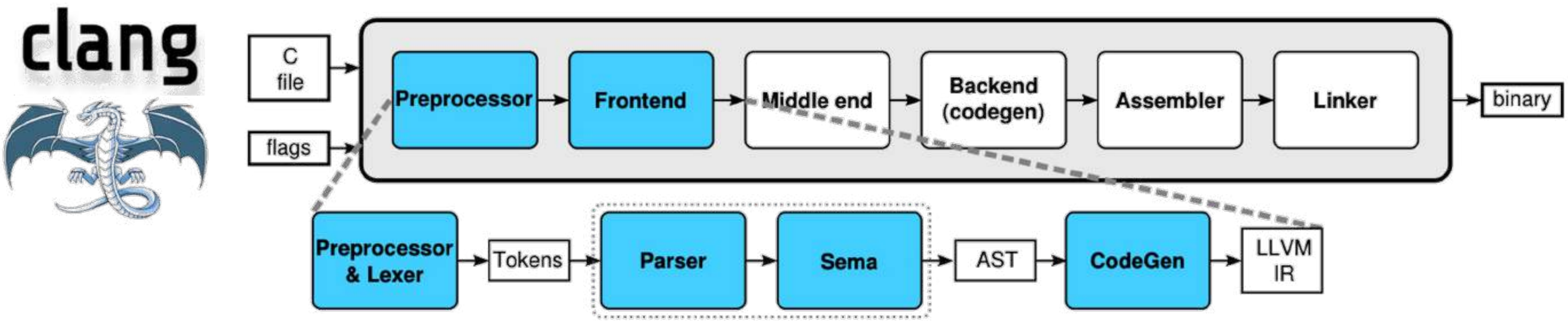
摘要： 针对目前编译实验教学过程中内容安排不够合理、与实际应用契合不够紧密的问题，提出基于 Clang/LLVM 面向业界实际的实验教学模式，通过分析目前课程现状及目标，阐述实验方案具体实施方法，最后通过对实验结果反馈的汇总，说明该实验设计更好地平衡了基础性、实践性和综合性，使得学生可以通过实际编译框架，更好的理解编译机制，掌握利用编译解决实际问题的能力，构建起编译实践的全局观。

关键词： 编译原理；系统实践；实验教学；Clang；LLVM

Lab[实验：编译器构造]



SYsU-lang

000_main.sysu.c

```c
int main(){
    return 3;
}
```

sysu-compiler

① lexer
② parser
③ generator
④ optimizer

a.S

```
        .text
        .file   "-"
        .globl  main                            // -- Begin function main
        .p2align        2
        .type   main,@function
main:                                   // @main
        .cfi_startproc
// %bb.0:                               // %entry
        mov     w0, #3
        ret
.Lfunc_end0:
        .size   main, .Lfunc_end0-main
        .cfi_endproc
                                        // -- End function
        .section        ".note.GNU-stack","",@progbits
```

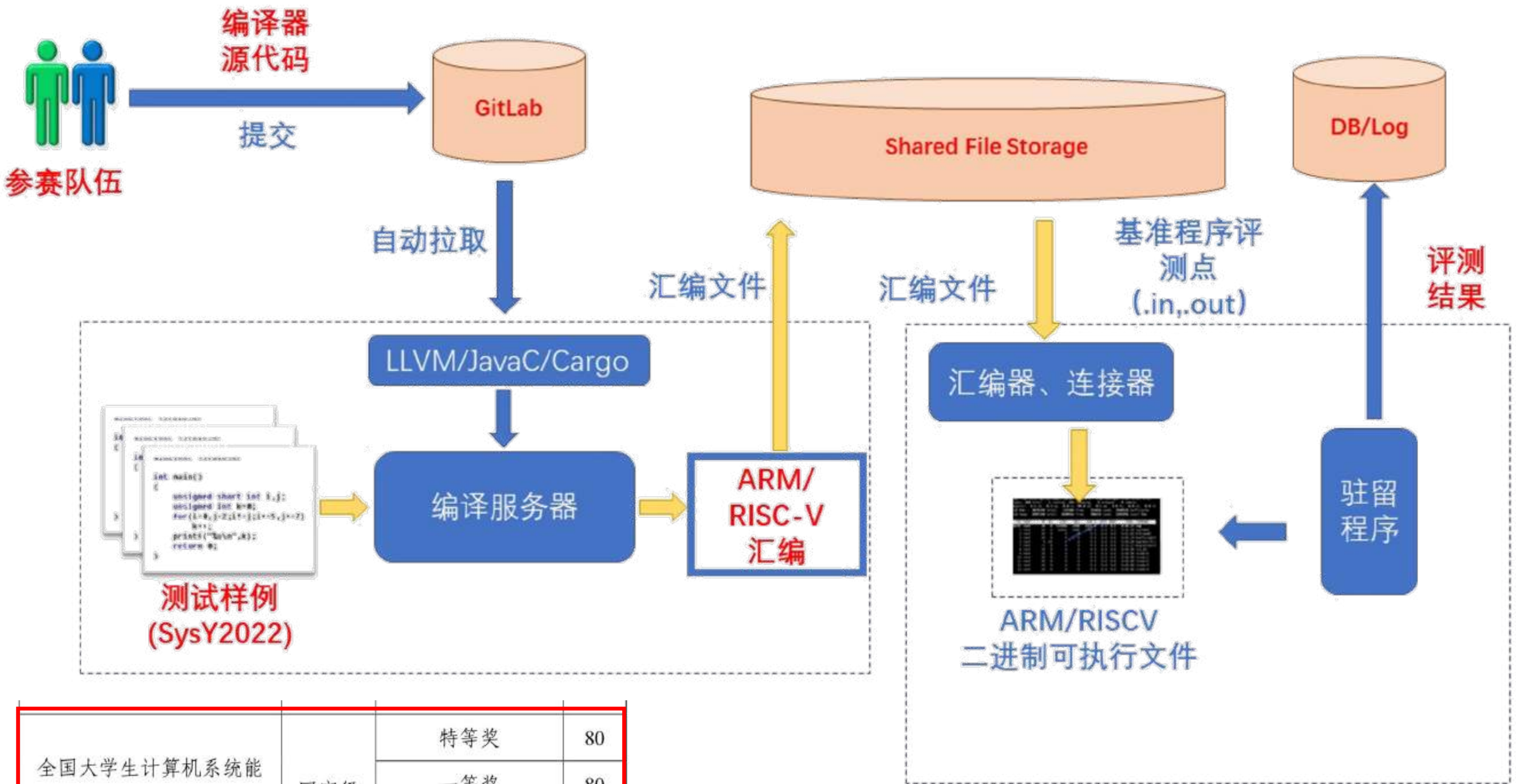
clang

executable

https://github.com/arcsysu/SYsU-lang2

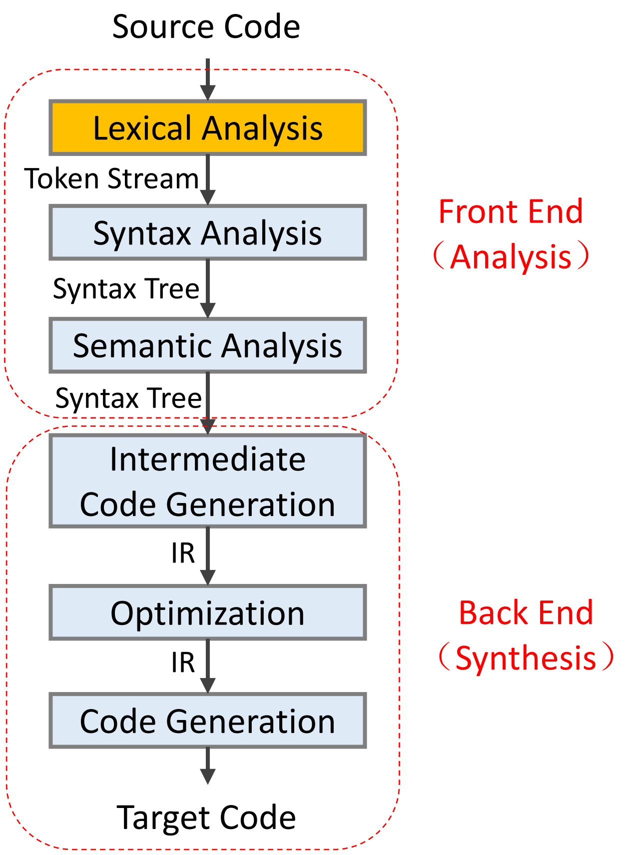
编译系统设计赛

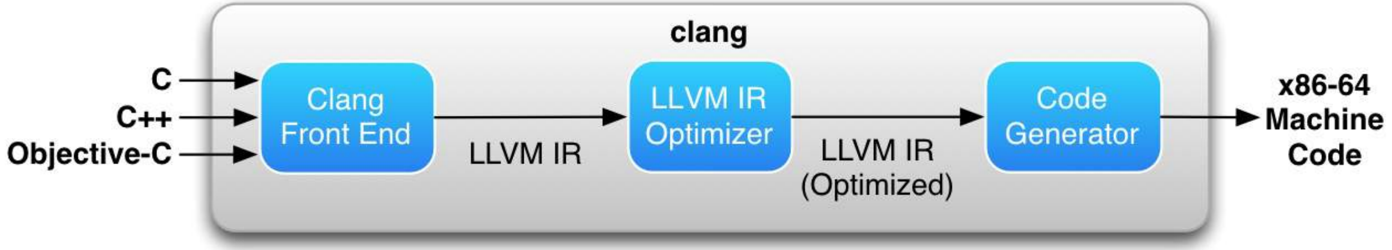
- 综合运用各种知识，构思并实现一个综合性编译系统



全国大学生计算机系统能力大赛	国家级	特等奖	80
		一等奖	80
		二等奖	20

Structure of a Typical Compiler[结构]





Example

```c
void main(){
  int a, b, c;
  if (b == c)
    return 1;
}
```

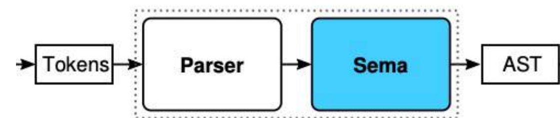
$clang -cc1 -dump-tokens test.c

```
void 'void'      [StartOfLine]  Loc=<parse.c:1:1>
identifier 'main'        [LeadingSpace] Loc=<parse.c:1:6>
l_paren '('             Loc=<parse.c:1:10>
r_paren ')'             Loc=<parse.c:1:11>
l_brace '{'             Loc=<parse.c:1:12>
int 'int'        [StartOfLine] [LeadingSpace]   Loc=<parse.c:2:3>
identifier 'a'   [LeadingSpace] Loc=<parse.c:2:7>
comma ','               Loc=<parse.c:2:8>
identifier 'b'   [LeadingSpace] Loc=<parse.c:2:10>
comma ','               Loc=<parse.c:2:11>
identifier 'c'   [LeadingSpace] Loc=<parse.c:2:13>
semi ';'                Loc=<parse.c:2:14>
if 'if'  [StartOfLine] [LeadingSpace]   Loc=<parse.c:3:3>
l_paren '('      [LeadingSpace] Loc=<parse.c:3:6>
identifier 'b'          Loc=<parse.c:3:7>
equalequal '=='  [LeadingSpace] Loc=<parse.c:3:9>
identifier 'c'   [LeadingSpace] Loc=<parse.c:3:12>
r_paren ')'             Loc=<parse.c:3:13>
return 'return'  [StartOfLine] [LeadingSpace]   Loc=<parse.c:4:5>
numeric_constant '1'     [LeadingSpace] Loc=<parse.c:4:12>
semi ';'                Loc=<parse.c:4:13>
r_brace '}'      [StartOfLine]  Loc=<parse.c:5:1>
eof ''          Loc=<parse.c:5:2>
```

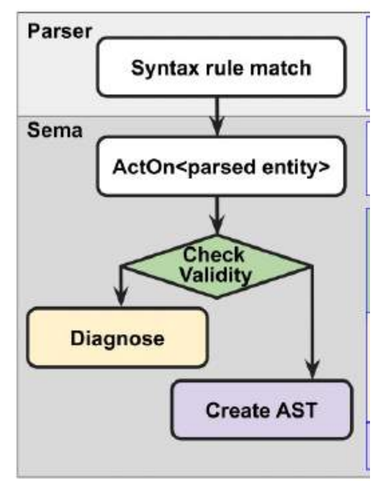
clang

$clang -Xclang -ast-dump -fsyntax-only test.c

```
`-FunctionDecl 0x27999470 <parse.c:1:1, line:5:1> line:1:6 main 'void ()'
  `-CompoundStmt 0x27999800 <col:12, line:5:1>
    |-DeclStmt 0x279996f8 <line:2:3, col:14>
    | |-VarDecl 0x27999570 <col:3, col:7> col:7 a 'int'
    | |-VarDecl 0x279995f0 <col:3, col:10> col:10 used b 'int'
    | `-VarDecl 0x27999670 <col:3, col:13> col:13 used c 'int'
    `-IfStmt 0x279997e8 <line:3:3, line:4:12>
      |-BinaryOperator 0x27999780 <line:3:7, col:12> 'int' '=='
      | |-ImplicitCastExpr 0x27999750 <col:7> 'int' <LValueToRValue>
      | | `-DeclRefExpr 0x27999710 <col:7> 'int' lvalue Var 0x279995f0 'b' 'int'
      | `-ImplicitCastExpr 0x27999768 <col:12> 'int' <LValueToRValue>
      |   `-DeclRefExpr 0x27999730 <col:12> 'int' lvalue Var 0x27999670 'c' 'int'
      `-ReturnStmt 0x279997d8 <line:4:5, col:12>
        `-ImplicitCastExpr 0x279997c0 <col:12> 'void' <ToVoid>
          `-IntegerLiteral 0x279997a0 <col:12> 'int' 1
```



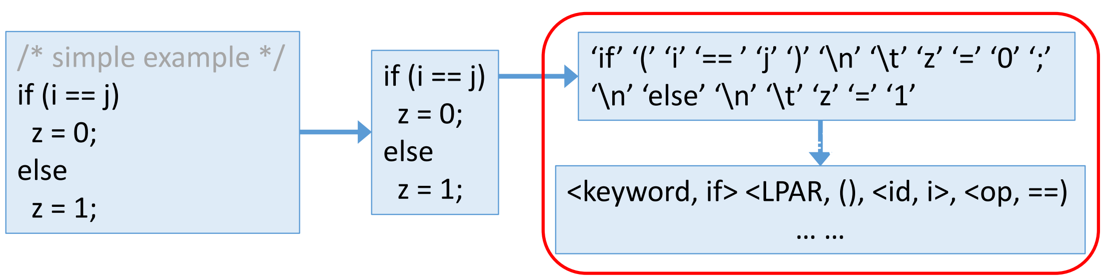
Sema is tight coupling with parser

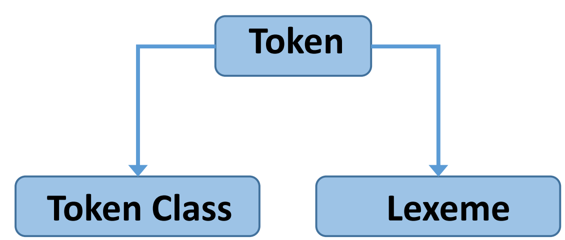


https://llvm.org/devmtg/2019-10/slides/ClangTutorial-Stulova-vanHaastregt.pdf

Lexical Analysis

- Workflow
  - Partition the input character stream to lexemes
  - Identify the token class of each lexeme
- **Regular Expression** is a good way to specify tokens
  - <u>Simple</u> yet powerful (able to express patterns)
- **Finite Automata** is to construct a token recognizer for languages given by regular expressions
  - A program for classifying tokens (accept, reject)

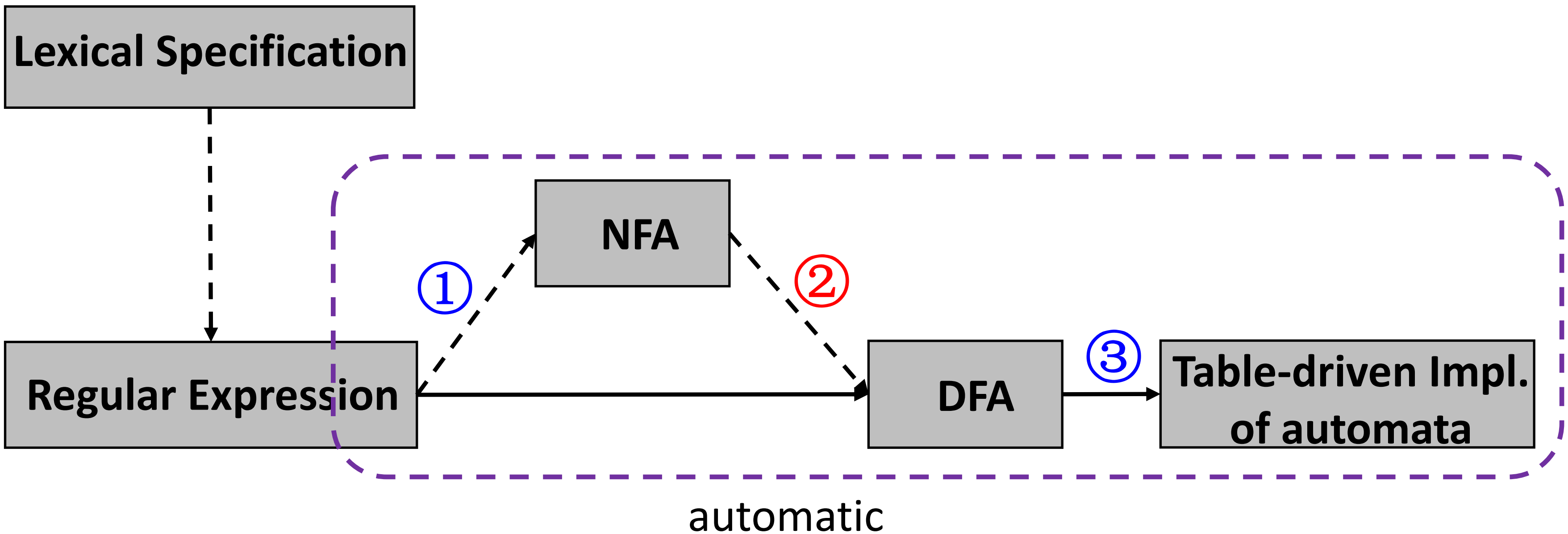




String patterns describing the class

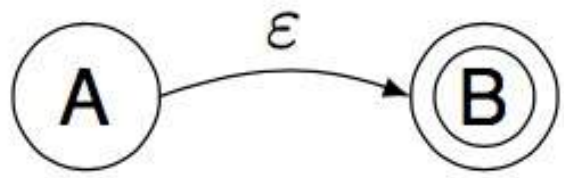
The Conversion Flow[转换流程]

- Outline: RE → NFA → DFA → Table-drive Implementation
  - ③ Converting DFAs to table-driven implementations
  - ① Converting REs to NFAs
  - ② Converting NFAs to DFAs



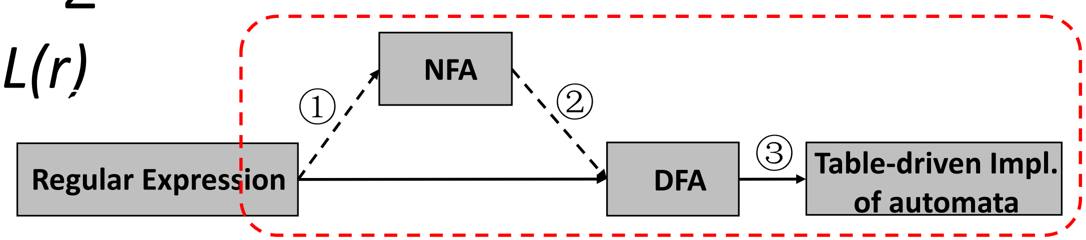
RE → NFA

- NFA can have ε-moves
  - Edges labelled with ε
  - Move from state *A* to state *B* without reading any input



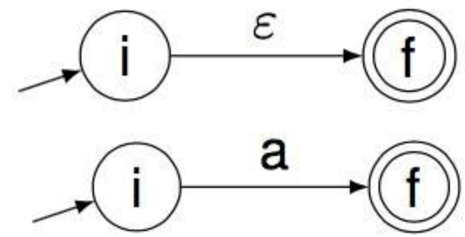
- **M-Y-T algorithm** (Thompson's construction) to convert any RE to an NFA that defines the same language[正则表达式转换到自动机]
  - Input: RE *r* over alphabet ∑
  - Output: NFA accepting *L(r)*

McNaughton-Yamada-Thompson

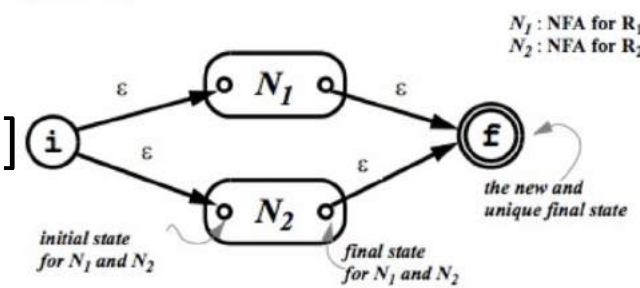


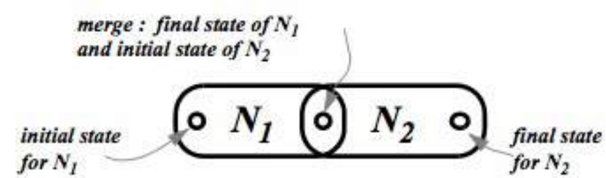
RE → NFA (cont.)

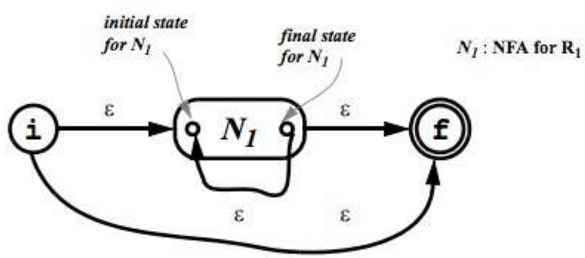
- Step 1: processing atomic REs
  - ε expression[空]
    - *i* is a new state, the start state of NFA
    - *f* is another new state, the accepting state of NFA
  - Single character RE *a*[单字符]



- Step 2: processing compound REs[组合]
  - $R = R_1 \mid R_2$
  - $R = R_1R_2$
  - $R = R_1{}^*$



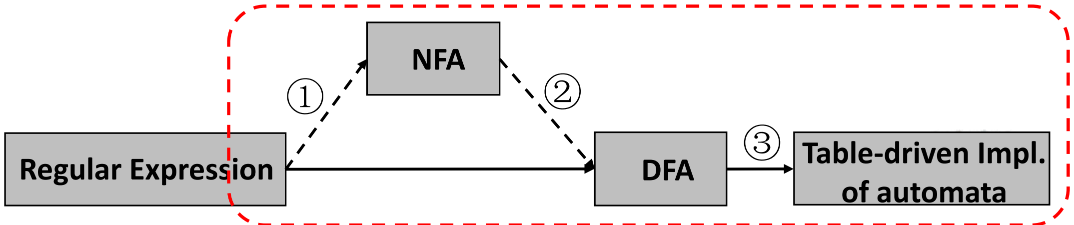




NFA → DFA: Idea

- Algorithm to convert[转换算法]
  - Input: an NFA *N*
  - Output: a DFA *D* accepting the same language as *N*

- **Subset construction**[子集构建]
  - Each state of the constructed DFA corresponds to a set of NFA states[一个DFA状态对应多个NFA状态]
    - Hence, the name 'subset construction'
  - After reading input $a_1a_2...a_n$, the DFA is in that state which corresponds to the set of states that the NFA can reach, from its start state, following paths labeled $a_1a_2...a_n$



NFA → DFA: Steps

- The **initial state** of the DFA is the set of all states the NFA can be in without reading any input[初始状态]
- For any state $\{q_i, q_j, \ldots, q_k\}$ of the DFA and any input *a*, the **next state** of the DFA is the set of all states of the NFA that can result as next states if the NFA is in any of the states $q_i, q_j, \ldots, q_k$ when it reads *a*[下一状态]
  - This includes states that can be reached by reading *a* followed by any number of ε-transitions
  - Use this rule to keep adding new states and transitions until it is no longer possible to do so
- The **accepting states** of the DFA are those states that contain an accepting state of the NFA[接收状态]

https://web.cse.msstate.edu/~hansen/classes/3813spring05/slides/04SubsetConstruction.pdf

NFA → DFA: Algorithm

Initially, ε-*closure*(s_0) is the only state in *Dstates* and it is unmarked

```
while there is an unmarked state T in Dstates do
    mark T
    for each input symbol a ∈ Σ do
        U := ε-closure(move(T,a))
        if U is not in Dstates then
            add U as an unmarked state to Dstates
        end if
        Dtran[T,a] := U
    end do
end do
```

- Operations on NFA states:
  - ε-closure(s): set of NFA states reachable from NFA state ***s*** on ε-transitions **alone**
  - ε-closure(T): set of NFA states reachable from some NFA state ***s*** in set ***T*** on ε-transitions **alone**; = $\cup_{s \text{ in } T}$ε-closure(s)
  - move(T, a): set of NFA states to which there is a transition on input symbol ***a*** from some state ***s*** in ***T***

Minimization Algorithm

- The algorithm
  - Partitioning the states of a DFA into groups of states that cannot be distinguished (i.e., equivalent)
  - Each groups of states is then merged into a single state of the min-state DFA

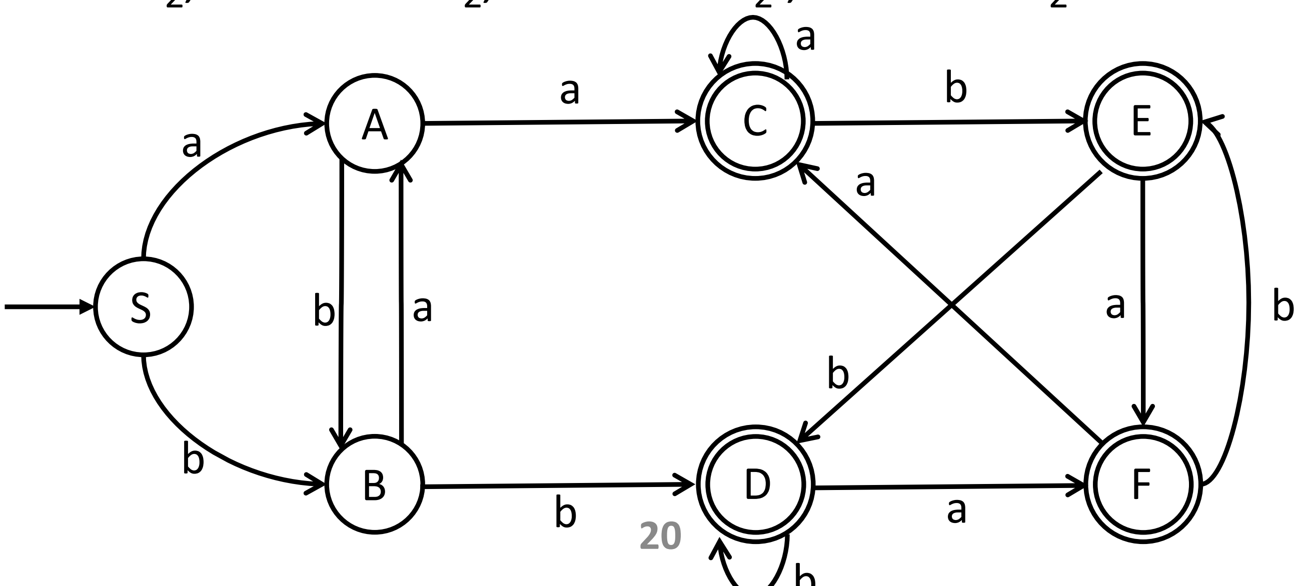
```
P <- {F}, {S - F}
while (P is still changing)
  T <- { }
   for each state s ∈ P
      for each α ∈ Σ
         partition s by α into s1 & s2
         T <- T ∪ s1 ∪ s2
   if T ≠ P then
      P <- T
```

- For a DFA（Σ, S, n, F, δ）
  - The initial partition P_0, has two sets and {*S* - *F*}
  - Splitting a set (i.e., partitioning a set by input symbol α)
    - Assume q_a and q_b ∈ ***s***, and $\delta(q_a, \alpha) = q_x$ and $\delta(q_b, \alpha) = q_y$
    - If q_x and q_y are not in the same set, then ***s*** must be split (i.e., α splits ***s***)
    - One state in the final DFA cannot have two transitions on α

https://people.cs.umass.edu/~moss/610-slides/06.pdf

Example

- P0: s_1 = {S, A, B}, s_2 = {C, D, E, F}
- For s_1, further splits into {S}, {A}, {B}
  - a: S --> A ∈ s_1, A --> C ∈ s_2, B --> A ∈ s_1 ⟹ a distincts s_1 => {S, B}, {A}
  - b: S --> B ∈ s_1, A --> B ∈ s_1, B --> D ∈ s_2 ⟹ b distincts s_1 => {S}, {B}, {A}
- For s_2, all states are equivalent
  - a: C --> C ∈ s_2, D --> F ∈ s_2, E --> F ∈ s_2 , F --> C ∈ s_2 ⟹ a doesn't
  - b: C --> E ∈ s_2, D --> D ∈ s_2, E --> D ∈ s_2 , F --> E ∈ s_2 ⟹ b doesn't

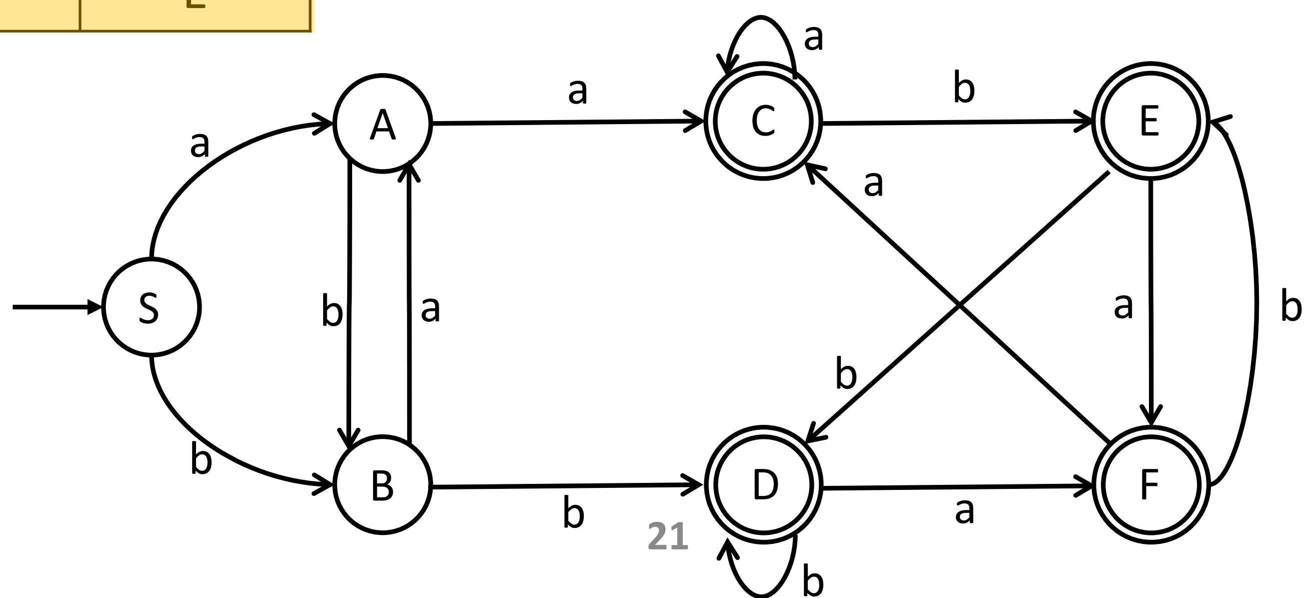


Example (cont.)

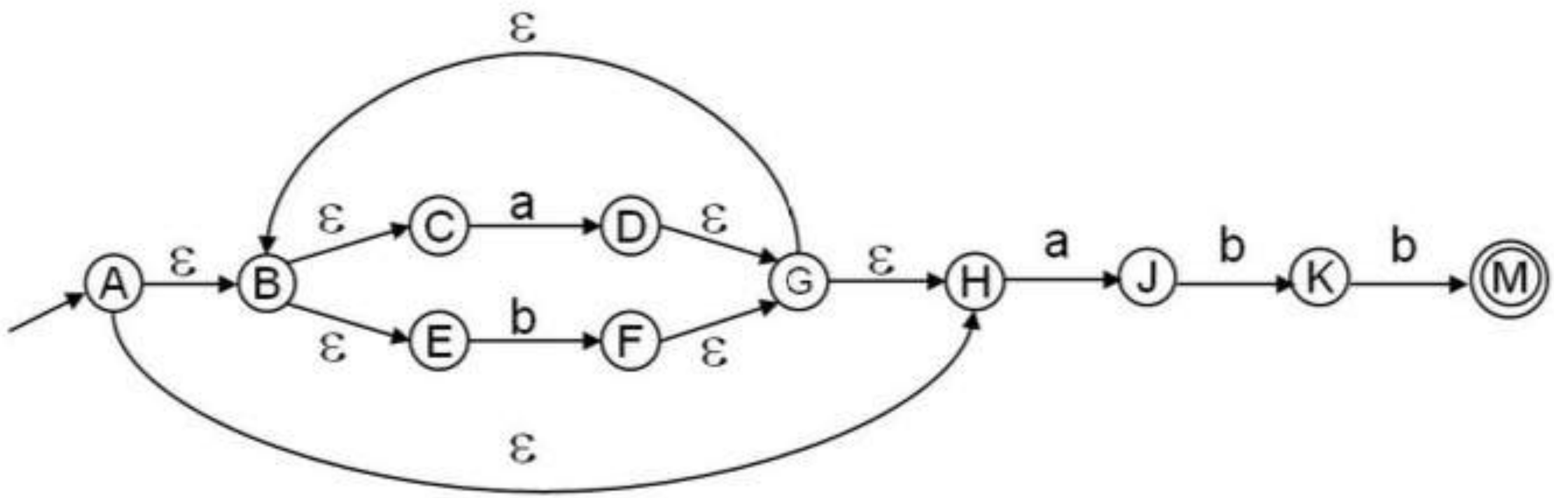
	a	b
S	A	B
A	C	B
B	A	D
C	C	E
D	F	D
E	F	D
F	C	E

	a	b
S	A	B
A	C	B
B	A	D
CF	C	E
DE	F	D

	a	b
S	A	B
A	C	B
B	A	D
CFDE	CF	DE



NFA → DFA: More Example

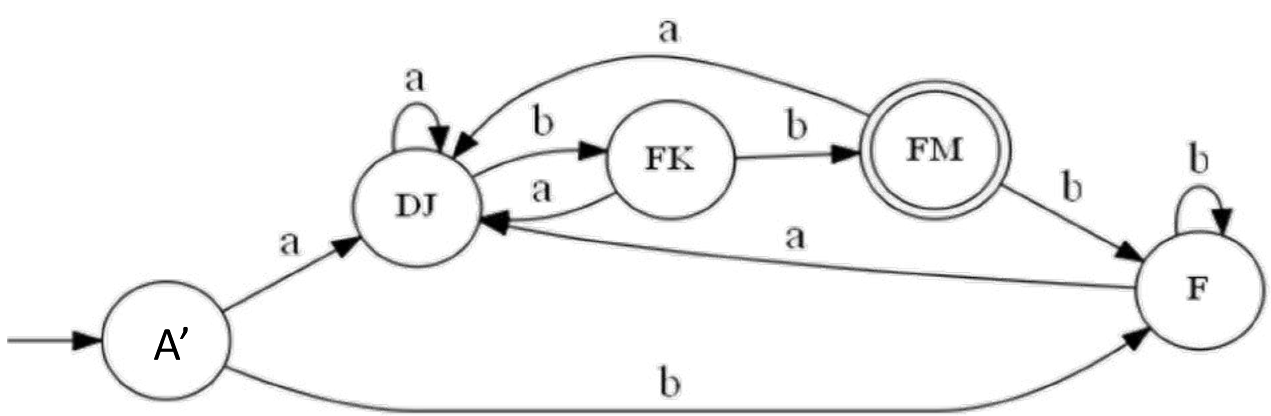


- Start state of the equivalent DFA
  - ε-closure(A) = {A, B, C, E, H} = A’
- ε-closure(move(A’, a)) = ε-closure({D, J}) = {B, C, D, E, H, G, J} = B’
- ε-closure(move(A’, b)) = ε-closure({F}) = {B, C, E , F, G, H} = C’
- … …

NFA → DFA: More Example (cont.)

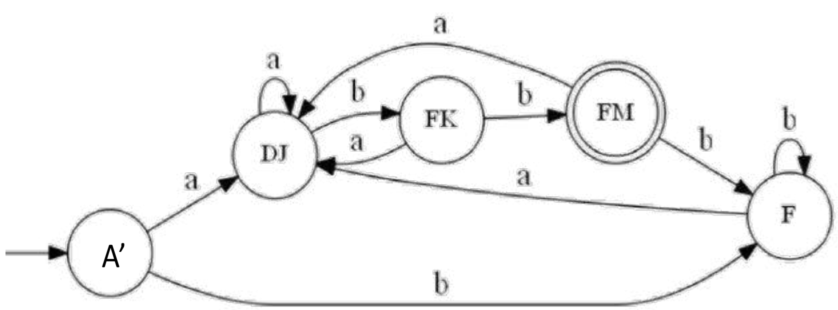
	a	b
A’	DJ	F
DJ	DJ	FK
F	DJ	F
FK	DJ	FM
FM	DJ	F

- Is the DFA minimal?
  - States A’ and F should be merged
- Should we merge states A’ and FM?
  - NO. A’ and FM are in different sets from the very beginning (FM is accepting, A’ is not).



NFA → DFA: More Example (cont.)

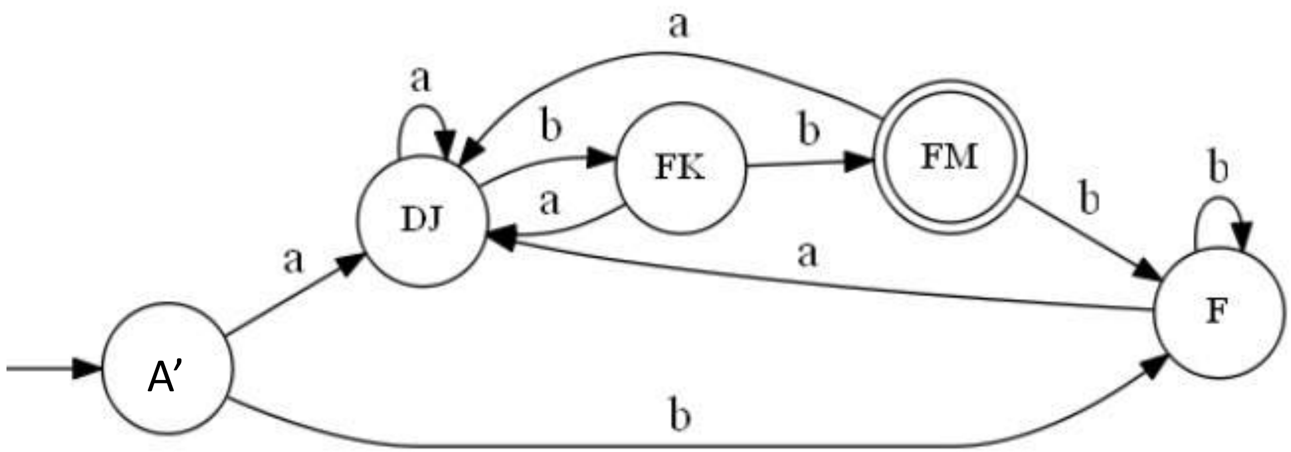
- P0: s_1 = {A', DJ, FK, F}, s_2 = {FM}
- For s_1, further splits into {A', DJ, F}, {FK}
  - a: A'--> DJ ∈ s_1, DJ --> DJ ∈ s_1, FK --> DJ ∈ s_1, F --> DJ ∈ s_1 ⟹ a doesn't distinct
  - b: A' --> F ∈ s_1, DJ --> FK ∈ s_1, FK --> FM ∈ s_2, F --> F ∈ s_1 ⟹ b distincts s_1 => s_{11}={A', DJ, F}, s_{12}={FK}
- For s_{11}, further splits into {A', DJ, F}, {FK}
  - a: A'--> DJ ∈ s_{11}, DJ --> DJ ∈ s_{11}, F --> DJ ∈ s_{11} ⟹ a doesn't distinct
  - b: A'--> F ∈ s_{11}, DJ --> FK ∈ s_{12}, F --> DJ ∈ s_{11} ⟹ b distincts s_{11} => s_{111}={A', F}, s_{112}={DJ}
- For s_{111}, impossible to further split
- Final states: S_{111} = {A', F}, S_{112} = {DJ}, S_{12} = {FK}, S_2 = {FM}



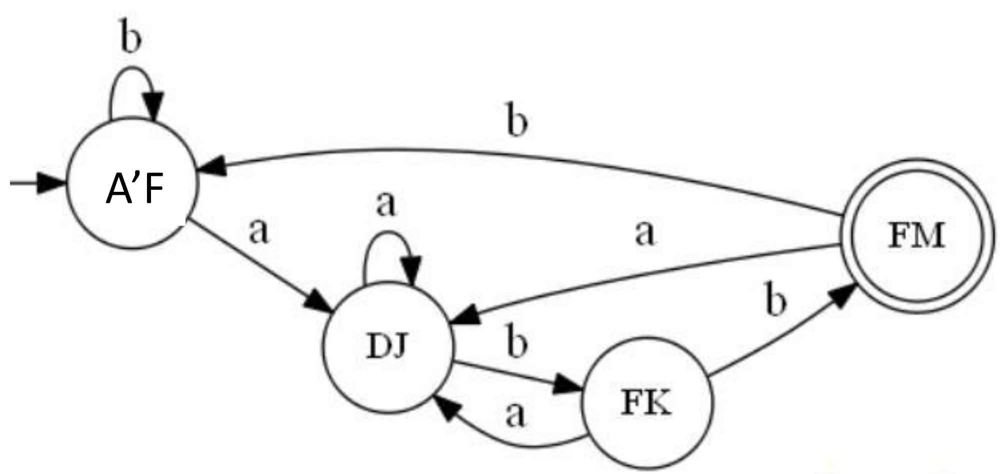
	a	b
A'	DJ	F
DJ	DJ	FK
F	DJ	F
FK	DJ	FM
FM	DJ	F

NFA → DFA: More Example (cont.)

- Original DFA: before merging A’ and F



- Minimized DFA: Do you see the original RE (a|b)*abb



The Conversion Flow[转换流程]

- Outline: RE → NFA → DFA → Table-drive Implementation
  - ③ Converting DFAs to table-driven implementations
  - ① Converting REs to NFAs (M-Y-T algorithm)
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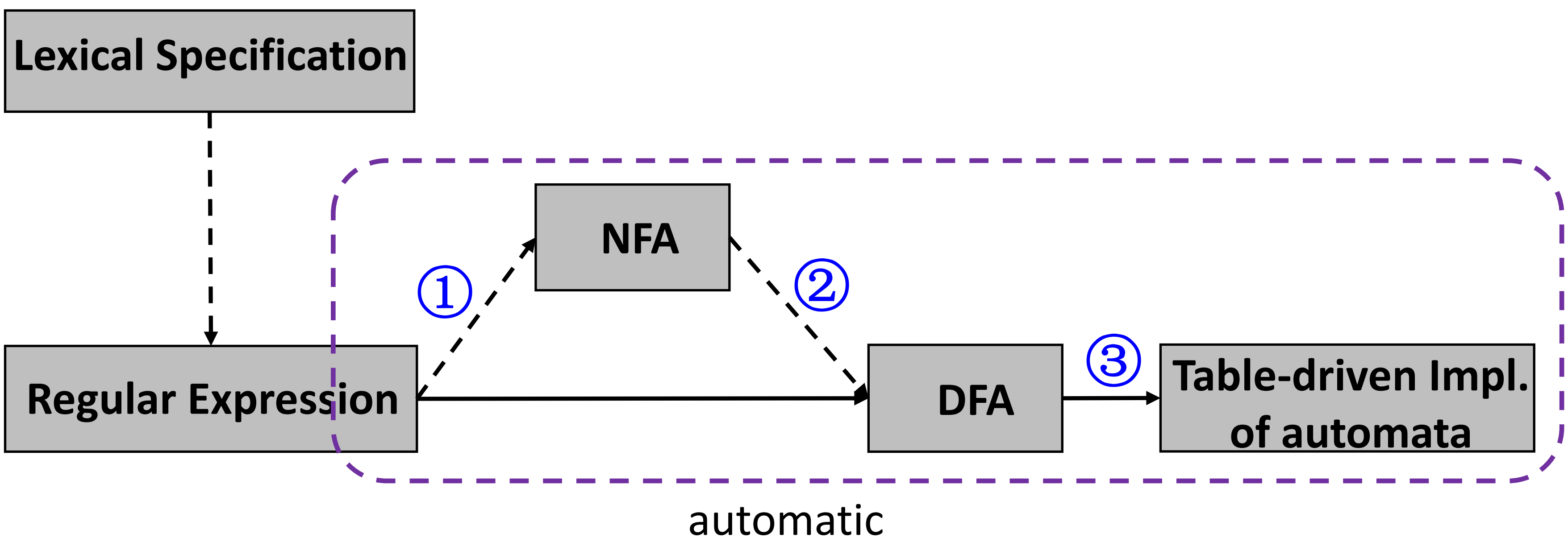


NFA → DFA: Space Complexity[空间复杂度]

- NFA may be in many states at any time
- How many different possible states in DFA?
  - If there are *N* states in NFA, the DFA must be in some subset of those *N* states
  - How many non-empty subsets are there?
    - 2^N-1
- The resulting DFA has $O(2^N)$ space complexity, where *N* is number of original states in NFA
  - For real languages, the NFA and DFA have about same number of states

NFA → DFA: Time Complexity[时间复杂度]

- DFA execution
  - Requires O(|X|) steps, where |X| is the input length
  - Each step takes constant time
    - If current state is *S* and input is *c*, then read T[*S*, *c*]
    - Update current state to state T[*S*, *c*]
  - Time complexity = O(|X|)

Deterministic: unique transition

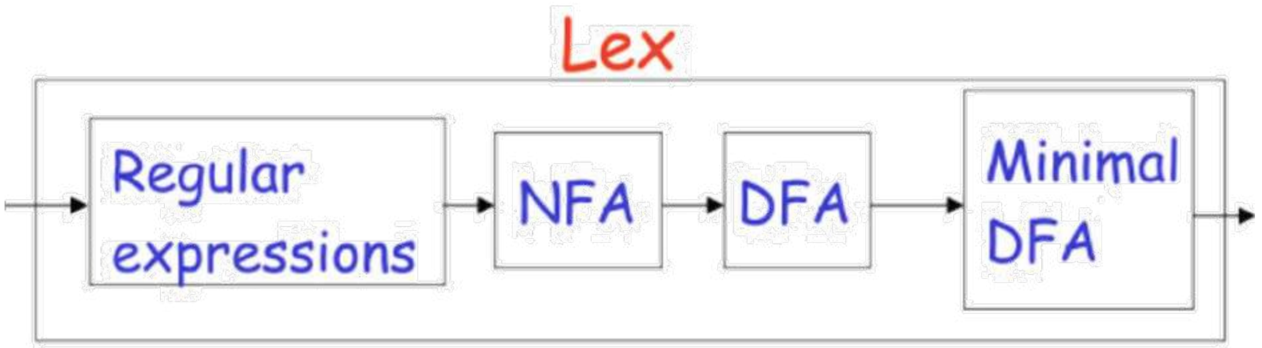
- NFA execution
  - Requires O(|X|) steps, where |X| is the input length
    - Anyway, the input symbols should be completely processed
  - Each step takes $O(N^2)$ time, where *N* is the number of states
    - Current state is a set of potential states, up to *N*
    - On input c, must union all $T[S_{potential}, c]$, up to *N* times
      - Each union operation takes O(N) time
  - Time complexity = $O(|X|*N^2)$

Non-deterministic: from current state, you can transit to any (including itself)

SUN YAT-SEN UNIVERSITY 中山大學

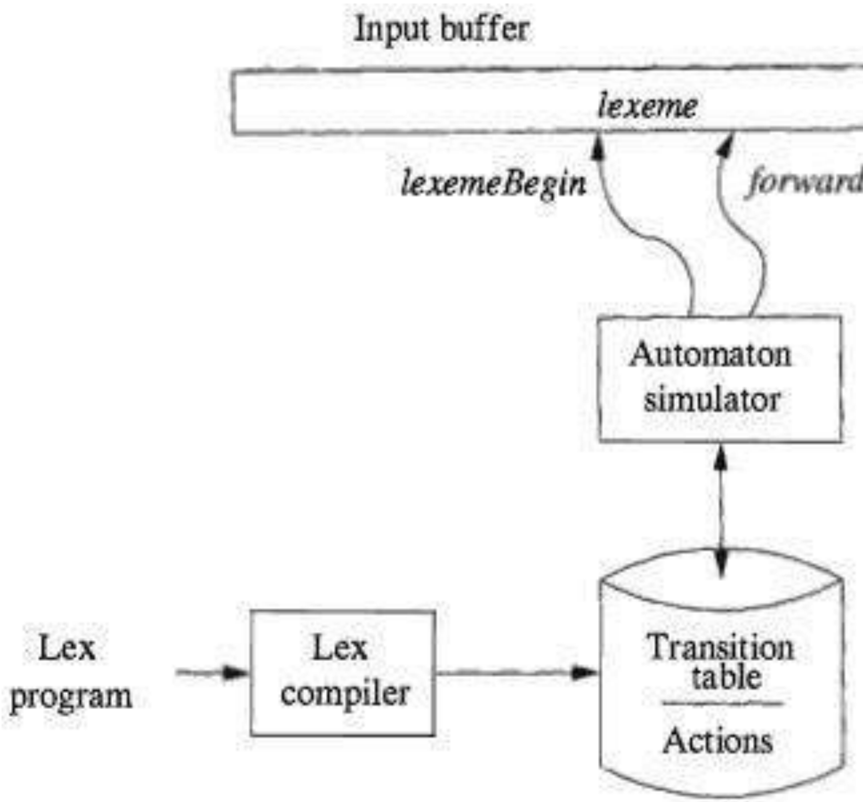
Implementation in Practice[实际实现]

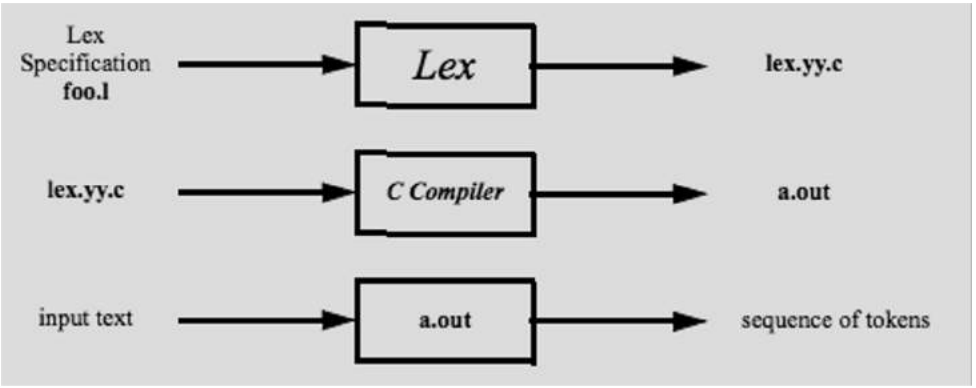
- Lex: RE → NFA → DFA → Table
  - Converts regular expressions to NFA
  - Converts NFA to DFA
  - Performs DFA state minimization to reduce space
  - Generate the transition table from DFA
  - Performs table compression to further reduce space
- Most other automated lexers also choose DFA over NFA
  - Trade off space for speed



Lexical Analyzer Generated by Lex

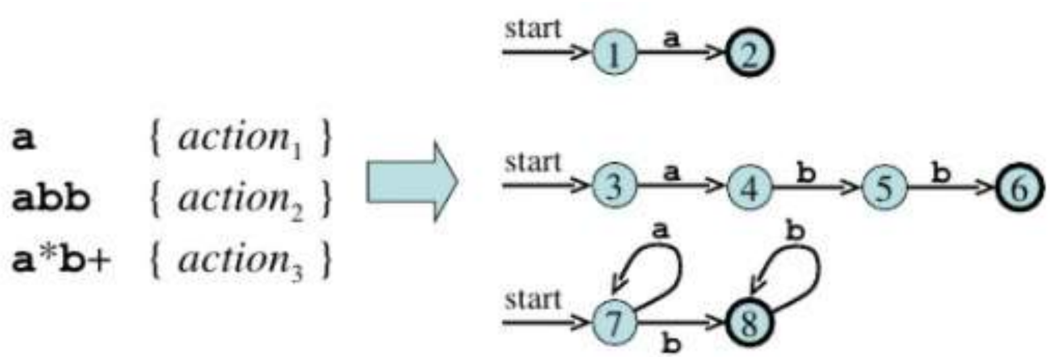
- A Lex program is turned into a transition table and actions, which are used by a FA simulator
- Automaton recognizes matching any of the patterns

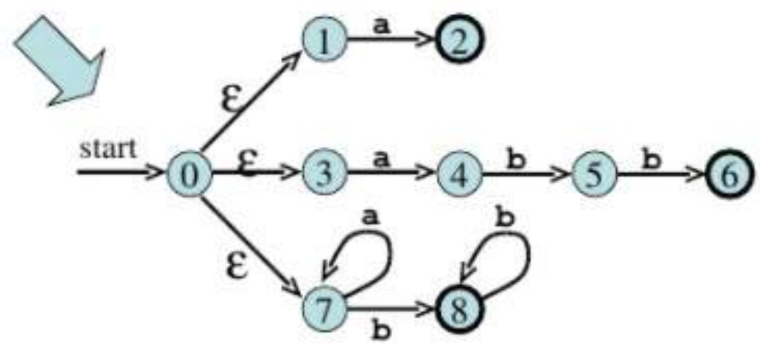




Lex: Example

- Three patterns, three NFAs
- Combine three NFAs into a single NFA
  - Add start state 0 and ε-transitions





Any one is possbile, if you haven’t read any input symbol ⟹

Lex: Example (cont.)

```
ptn1    a
ptn2    abb
ptn3    a*b+

%%

{ptn1}  { printf("\n<%s, %s>", "ptn1", yytext); }
{ptn2}  { printf("\n<%s, %s>", "ptn2", yytext); }
{ptn3}  { printf("\n<%s, %s>", "ptn3", yytext); }

%%

int main(){
  yylex();
  return 0;
}
```

$flex lex.l

$clang lex.yy.c -o mylex -ll

```
root@aa51dde06c76:~/test# echo "aaba" | ./mylex

<ptn3, aab>
<ptn1, a>
root@aa51dde06c76:~/test# echo "abba" | ./mylex

<ptn2, abb>
<ptn1, a>
```

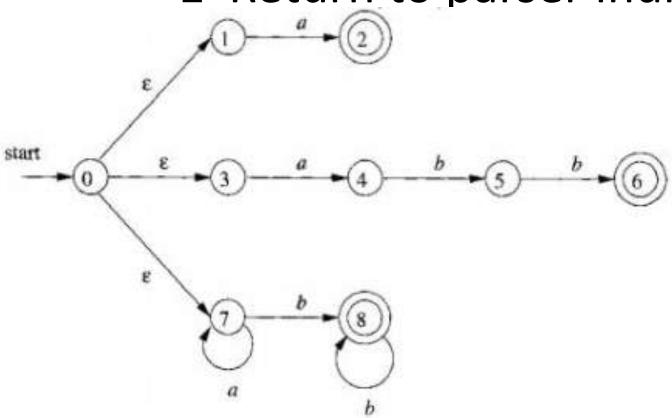
Lex: Example (cont.)

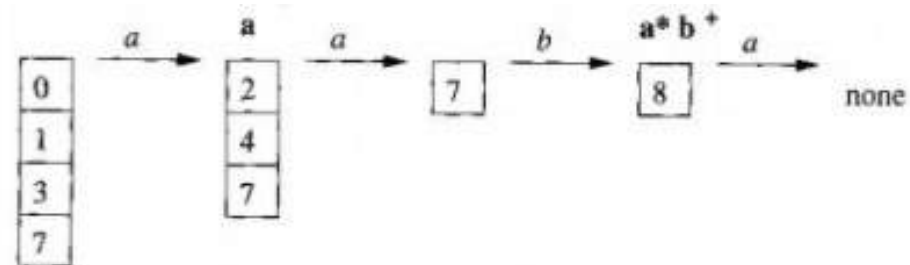
- NFA's for lexical analyzer
- Input: aaba
  - ε-closure(0) = {0, 1, 3, 7}
  - Empty states after reading the fourth input symbol
    - There are no transitions out of state 8
    - Back up, looking for a set of states that include an accepting state
  - State 8: a*b+ has been matched
    - Select aab as the lexeme, execute $action_3$
    - Return to parser indicating that token w/ pattern p_3=a*b+ has been found

a

abb

a*b+



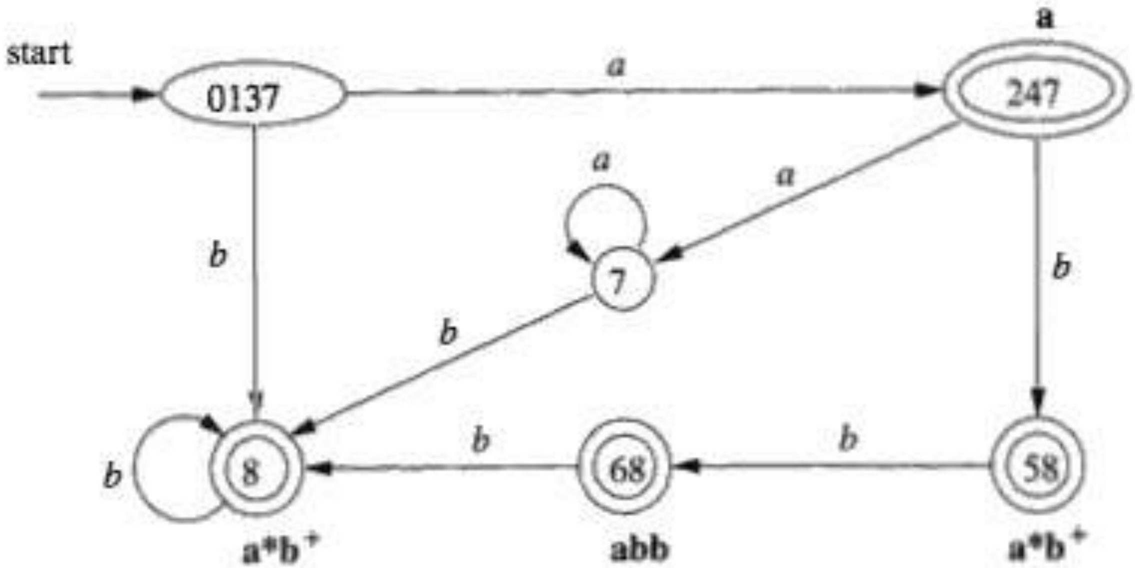


aaba → (a*b+, aab), (a, a)

Lex: Example (cont.)

- DFA's for lexical analyzer
- Input: abba
  - Sequence of states entered: 0137 → 247 → 58 → 68
  - At the final *a*, there is no transition out of state 68
    - 68 itself is an accepting state that reports pattern p_2 = abb

a
abb
a*b+



How Much Should We Match?[匹配多少]

- In general, find the longest match possible
  - We have seen examples
  - One more example: input string aabbb …
    - Have many prefixes that match the third pattern
    - Continue reading *b*'s until another *a* is met
    - Report the lexeme to be the intial *a*'s followed by as many *b*'s as there are

a	{ $action_1$ }
abb	{ $action_2$ }
a*b+	{ $action_3$ }

- If same length, rule appearing first takes precedence
  - String *abb* matches both the second and third
  - We consider it as a lexeme for p_2, since that pattern listed first

```
ptn1    a
ptn2    abb
ptn3    a*b+

%%

{ptn1}  { printf("\n<%s, %s>", "ptn1", yytext); }
{ptn2}  { printf("\n<%s, %s>", "ptn2", yytext); }
{ptn3}  { printf("\n<%s, %s>", "ptn3", yytext); }
```

<ptn2, abb>

```
ptn1    a
ptn2    abb
ptn3    a*b+

%%

{ptn1}  { printf("\n<%s, %s>", "ptn1", yytext); }
{ptn3}  { printf("\n<%s, %s>", "ptn3", yytext); }
{ptn2}  { printf("\n<%s, %s>", "ptn2", yytext); }
```

<ptn3, abb>

How to Match Keywords?[匹配关键字]

- Example: to recognize the following tokens
  - Identifiers: letter(letter|digit)*
  - Keywords: if, then, else
- **Approach 1**: make REs for keywords and place them before REs for identifiers so that they will take precedence
  - Will result in more bloated finite state machine
- **Approach 2**: recognize keywords and identifiers using same RE but differentiate using special keyword table
  - Will result in more streamlined finite state machine
  - But extra table lookup is required
- Usually approach 2 is more efficient than 1, but you can implement approach 1 in your projects for simplicity

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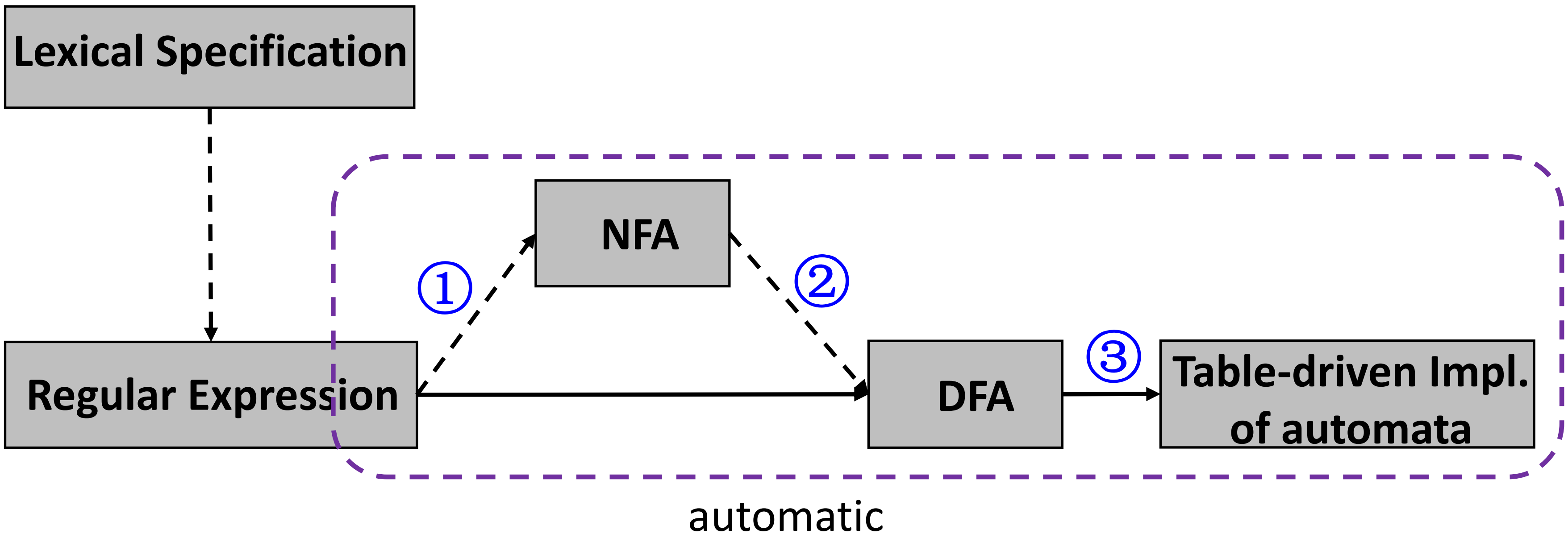

Beyond Regular Languages

- Regular languages are expressive enough for tokens
  - Can express identifiers, strings, comments, etc.
- However, it is the weakest (least expressive) language
  - Many languages are not regular
  - C programming language is not
    - The language matching braces "{{{...}}}" is also not
  - FA cannot count # of times char encountered
    - $L = \{a^n b^n \mid n \geq 1\}$
    - Crucial for analyzing languages with nested structures (e.g. nested for loop in C language)
- We need a more powerful language for parsing
  - Later, we will discuss context-free languages (CFGs)