Context-Free Grammars

Second Midterm Logistics

- Our second midterm exam is ***Tuesday, May 19th*** from ***7-9 pm***. Check Ed or the exam page for seating assignments.
- Topic coverage is primarily lectures 06 – 16 (functions through DFAs & NFAs) and PS3 – PS6.
  - Because the material is cumulative, topics from PS1 – PS2 and Lectures 00 – 05 are also fair game.
- The exam is closed-book and closed-computer. You can bring one double-sided 8.5” × 11” sheet of notes with you.

Recap from Last Time

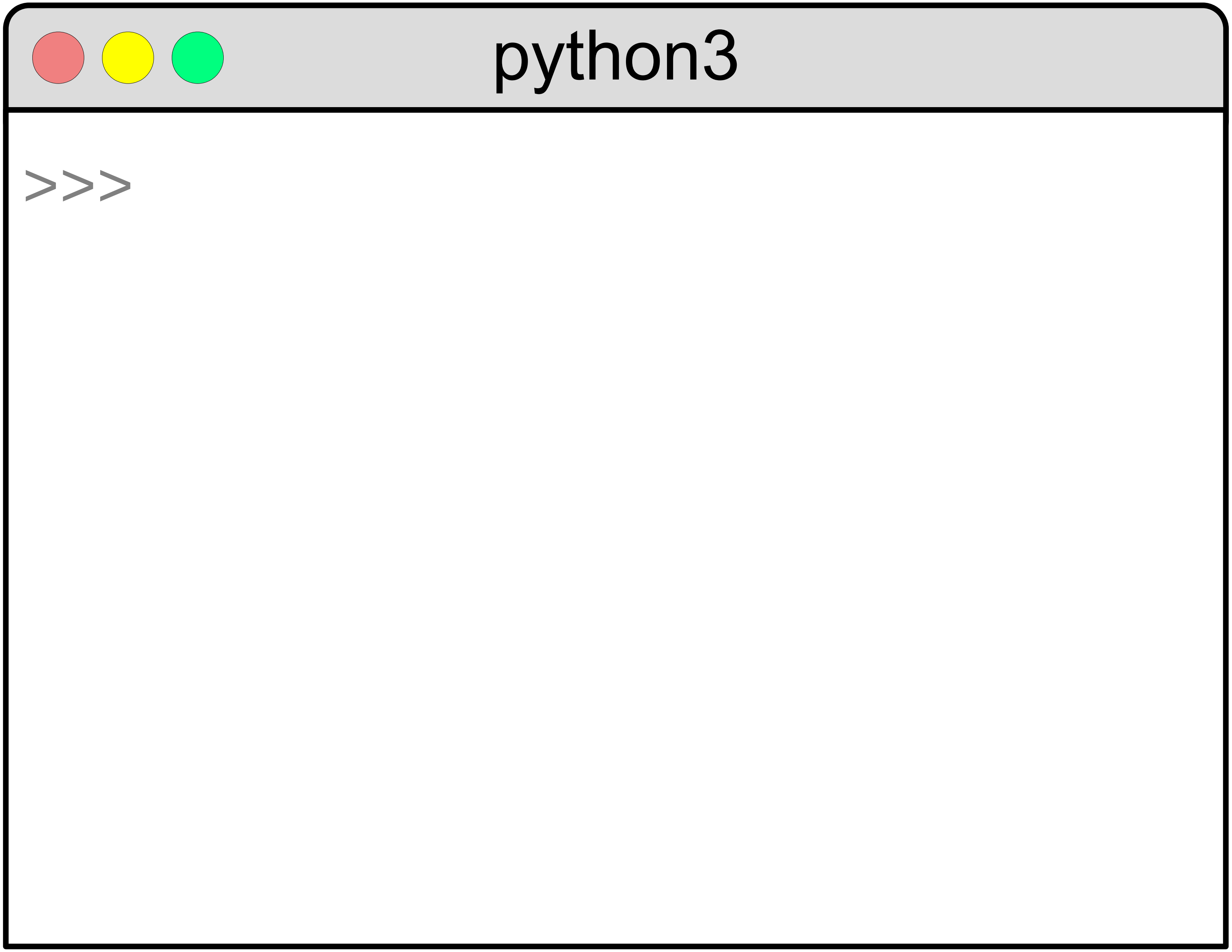
- If L is a language and S is a distinguishing set for L that contains infinitely many strings, then L is not regular

- Distinguishing set: A set of strings, each of which represent information that requires a distinct state to represent it
  - e.g., “we've seen 2 a's, we've seen 3 a's, ...”

- Infinitely many strings in a distinguishing set implies there is no finite number of states that can represent all the required information.

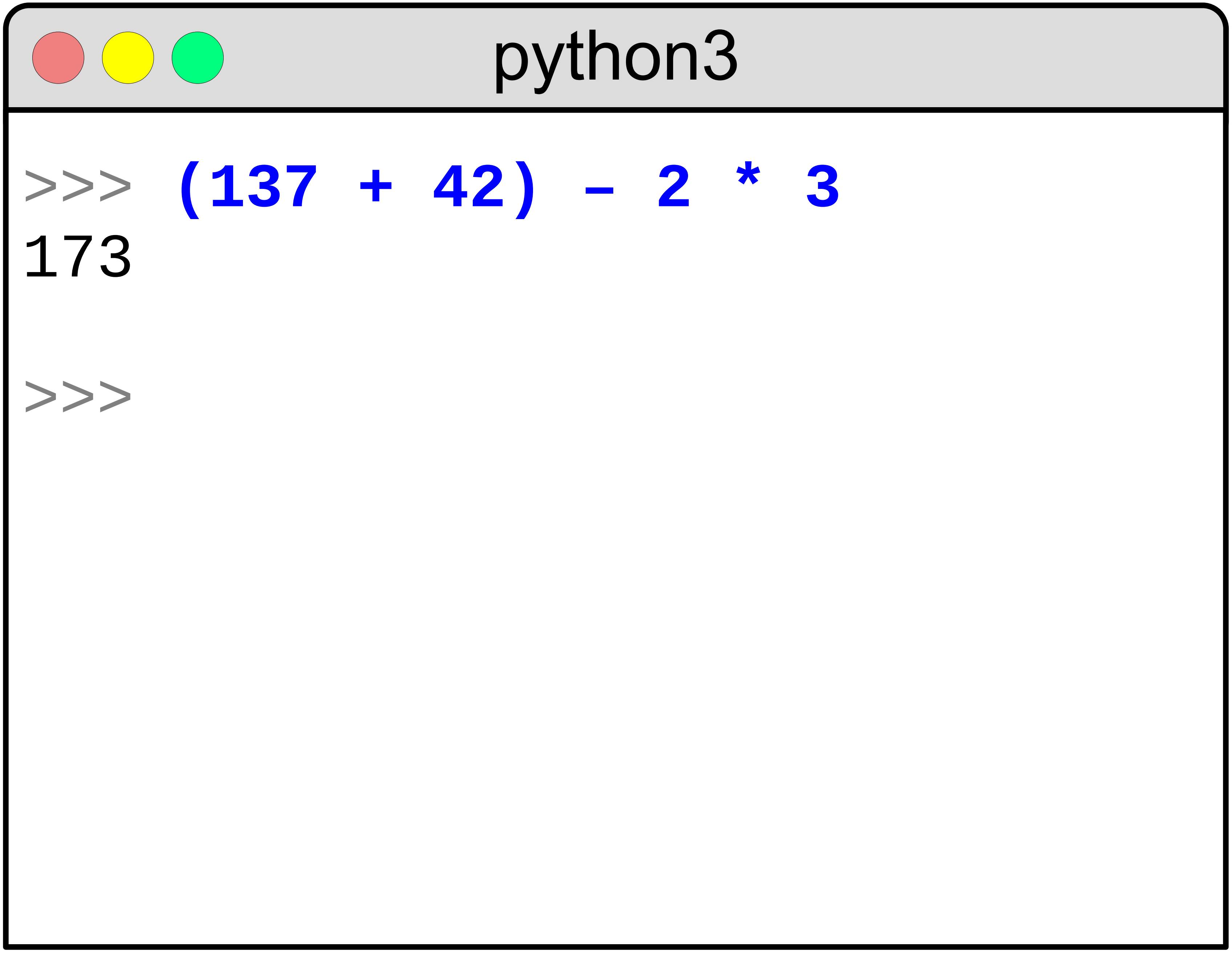
New Stuff

A Motivating Question


python3
>>>

python3

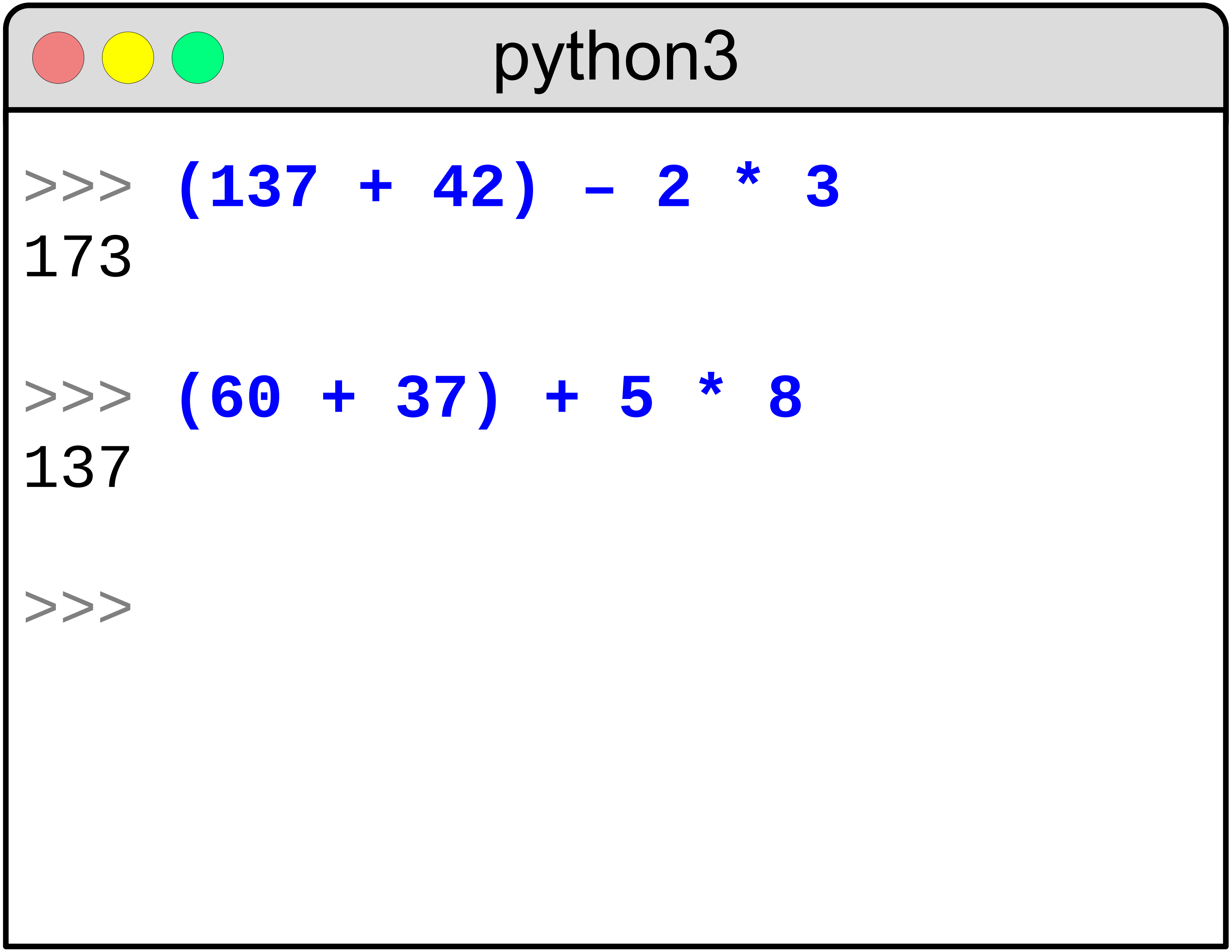
```
>>> (137 + 42) - 2 * 3
```


python3
>>> (137 + 42) - 2 * 3
173
>>>

python3

```
>>> (137 + 42) - 2 * 3
173

>>> (60 + 37) + 5 * 8
```


python3
>>> (137 + 42) - 2 * 3
173
>>> (60 + 37) + 5 * 8
137
>>>

python3

```
>>> (137 + 42) - 2 * 3
173

>>> (60 + 37) + 5 * 8
137

>>> (200 / 2) + 6 / 2
```

python3

```
>>> (137 + 42) - 2 * 3
173

>>> (60 + 37) + 5 * 8
137

>>> (200 / 2) + 6 / 2
103.0

>>>
```

Mad Libs for Arithmetic

(______ ______ ______) ______ ______ ______ ______

Int Op Int Op Int Op Int

Slide credit: Amy Liu

Mad Libs for Arithmetic

(	26	+	42	)	*	2	+	1
	Int	Op	Int		Op	Int	Op	Int

Slide credit: Amy Liu

Mad Libs for Arithmetic

(______ ______ ______) ______ ______ ______ ______

Int Op Int Op Int Op Int

Slide credit: Amy Liu

Mad Libs for Arithmetic

(	7	*	5	)	/	5	-	49
	Int	Op	Int		Op	Int	Op	Int

Slide credit: Amy Liu

Mad Libs for Arithmetic

(___ ___ ___) ___ ___ ___ ___

Int **Op** **Int** **Op** **Int** **Op** **Int**

This only lets us make arithmetic expressions of the form **(Int Op Int) Op Int Op Int**.

What about arithmetic expressions that don't follow this pattern?

Slide credit: Amy Liu

Recursive Mad Libs

______

Expr

Recursive Mad Libs

Expr

What can an arithmetic expression be?

Recursive Mad Libs

$$\frac{\texttt{int}}{\textbf{Expr}}$$

What can an arithmetic expression be?

`int`	A single number.

Recursive Mad Libs

______

Expr

What can an arithmetic expression be?

`int` A single number.

Recursive Mad Libs

Expr

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.

Recursive Mad Libs

___ ___ ___
Expr **Op** **Expr**

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.

Recursive Mad Libs

int

Expr **Op** **Expr**

What can an arithmetic expression be?

int	A single number.
Expr Op Expr	Two expressions joined by an operator.

Recursive Mad Libs

`int` `+`

Expr Op Expr

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.

Recursive Mad Libs

int	+	
Expr	**Op**	**Expr**

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.

Recursive Mad Libs

`int` `+`

Expr **Op** **Expr** **Op** **Expr**

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.

Recursive Mad Libs

`int`	`+`			
Expr	**Op**	**Expr**	**Op**	**Expr**

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.

Recursive Mad Libs

`int`	`+`	`int`		
Expr	**Op**	**Expr**	**Op**	**Expr**

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.

Recursive Mad Libs

`int`	`+`	`int`	`×`	
Expr	**Op**	**Expr**	**Op**	**Expr**

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.

Recursive Mad Libs

int	+	int	×	int
Expr	**Op**	**Expr**	**Op**	**Expr**

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.

Recursive Mad Libs

Expr

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.

Recursive Mad Libs

______

Expr

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.
(Expr)	A parenthesized expression.

Recursive Mad Libs

(______)
Expr

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.
(Expr)	A parenthesized expression.

Recursive Mad Libs

(____)

Expr

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.
`(`Expr`)`	A parenthesized expression.

Recursive Mad Libs

(______ ______ ______)

Expr **Op** **Expr**

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.
`(`**Expr**`)`	A parenthesized expression.

Recursive Mad Libs

(______ ______ ______)

Expr Op Expr

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.
(Expr)	A parenthesized expression.

Recursive Mad Libs

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.
(Expr)	A parenthesized expression.

Recursive Mad Libs

(int /)

Expr Op Expr

What can an arithmetic expression be?

int	A single number.
Expr Op Expr	Two expressions joined by an operator.
(Expr)	A parenthesized expression.

Recursive Mad Libs

`( int / ___ )`

Expr Op **Expr**

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.
`(` **Expr** `)`	A parenthesized expression.

Recursive Mad Libs

(int / (____))

Expr Op Expr

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.
`(`**Expr**`)`	A parenthesized expression.

Recursive Mad Libs

(**int** / (____))

Expr **Op** **Expr**

What can an arithmetic expression be?

int	A single number.
Expr Op Expr	Two expressions joined by an operator.
(Expr)	A parenthesized expression.

Recursive Mad Libs

(int / (____))

Expr   Op   Expr

What can an arithmetic expression be?

int	A single number.
Expr Op Expr	Two expressions joined by an operator.
(Expr)	A parenthesized expression.

Recursive Mad Libs

(int / (___ ___ ___))

Expr Op Expr Op Expr

What can an arithmetic expression be?

int	A single number.
Expr Op Expr	Two expressions joined by an operator.
(Expr)	A parenthesized expression.

Recursive Mad Libs

```
(int    /    (____  ____  ____))
 Expr   Op    Expr  Op    Expr
```

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.
`(`**Expr**`)`	A parenthesized expression.

Recursive Mad Libs

(int / (int ______ ______))

Expr Op Expr Op Expr

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.
(Expr)	A parenthesized expression.

Recursive Mad Libs

`( int / ( int + ____ ) )`

Expr Op Expr Op Expr

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.
`(`**Expr**`)`	A parenthesized expression.

Recursive Mad Libs

`( int / ( int + int ) )`

Expr Op Expr Op Expr

What can an arithmetic expression be?

`int`	A single number.
Expr Op Expr	Two expressions joined by an operator.
`(`**Expr**`)`	A parenthesized expression.

A ***context-free grammar*** (or ***CFG***) is a recursive set of rules that define a language.

More on the details of these rules in a bit.

Warning: CFGs are not finite automata – be prepared for something completely different!

Arithmetic Expressions

- Here's how we might express the recursive rules from earlier as a CFG.

Expr → `int`
Expr → **Expr Op Expr**
Expr → `(`**Expr**`)`
Op → `+`
Op → `-`
Op → `×`
Op → `/`

This is called a ***production rule***. It says "if you see **Expr**, you can replace it with **Expr Op Expr**."

Arithmetic Expressions

- Here's how we might express the recursive rules from earlier as a CFG.

Expr → `int`

Expr → **Expr Op Expr**

Expr → `(`**Expr**`)`

Op → `+`

Op → `-`

Op → `×`

Op → `/`

This one says "if you see **Op**, you can replace it with `-`."

Arithmetic Expressions

- Here's how we might express the recursive rules from earlier as a CFG.

Expr → `int`

Expr → **Expr Op Expr**

Expr → `(`**Expr**`)`

Op → `+`

Op → `-`

Op → `×`

Op → `/`

Expr

⇒ **Expr Op Expr**

⇒ **Expr Op** `int`

⇒ `int` **Op** `int`

⇒ `int / int`

Arithmetic Expressions

- Here's how we might express the recursive rules from earlier as a CFG.

Expr → `int`

Expr → **Expr Op Expr**

Expr → `(`**Expr**`)`

Op → `+`

Op → `-`

Op → `×`

Op → `/`

Expr

⇒ **Expr Op Expr**

⇒ **Expr Op** `int`

⇒ `int` **Op** `int`

⇒ `int / int`

These red symbols are called ***nonterminals***. They're placeholders that get expanded later on.

Arithmetic Expressions

- Here's how we might express the recursive rules from earlier as a CFG.

Expr → `int`

Expr → **Expr Op Expr**

Expr → `(`**Expr**`)`

Op → `+`

Op → `-`

Op → `×`

Op → `/`

Expr

⇒ **Expr Op Expr**

⇒ **Expr Op** `int`

⇒ `int` **Op** `int`

⇒ `int / int`

The symbols in blue monospace are **`terminals`**. They're the final characters used in the string and never get replaced.

Arithmetic Expressions

- Here's how we might express the recursive rules from earlier as a CFG.

Expr → `int`

Expr → **Expr Op Expr**

Expr → `(`**Expr**`)`

Op → `+`

Op → `-`

Op → `×`

Op → `/`

Expr
⇒ **Expr Op Expr**
⇒ **Expr Op** `(`**Expr**`)`
⇒ **Expr Op** `(`**Expr Op Expr**`)`
⇒ **Expr** `×` `(`**Expr Op Expr**`)`
⇒ `int` `×` `(`**Expr Op Expr**`)`
⇒ `int` `×` `(int` **Op Expr**`)`
⇒ `int` `×` `(int` **Op** `int)`
⇒ `int` `×` `(int + int)`

Context-Free Grammars

- Formally, a context-free grammar is a collection of four items:
  - a set of ***nonterminal symbols*** (sometimes called ***variables***),
  - a set of ***terminal symbols*** (the ***alphabet*** of the CFG),
  - a set of ***production rules*** saying how each nonterminal can be replaced by a string of terminals and nonterminals, and
  - a ***start symbol*** (which must be a nonterminal) that begins the derivation. By convention, the start symbol is the one on the left-hand side of the first production.

Expr → `int`
Expr → **Expr Op Expr**
Expr → `(`**Expr**`)`
Op → `+`
Op → `-`
Op → `×`
Op → `/`

Some CFG Notation

- In today’s slides, capital letters in **Bold Red Uppercase** represent nonterminals.
  - e.g. **A**, **B**, **C**, **D**
- Lowercase letters in **`blue monospace`** represent terminals.
  - e.g. **`t`**, **`u`**, **`v`**, **`w`**
- Lowercase Greek letters in ***gray italics*** represent arbitrary strings of terminals and nonterminals.
  - e.g. ***α***, ***γ***, ***ω***
- You don't need to use these conventions on your own; just make sure whatever you do is readable. 😃

A Notational Shorthand

Expr → `int`

Expr → **Expr Op Expr**

Expr → `(`**Expr**`)`

Op → `+`

Op → `-`

Op → `×`

Op → `/`

A Notational Shorthand

Expr → `int` | **Expr Op Expr** | `(`**Expr**`)`

Op → `+` | `-` | `×` | `/`

Derivations

Expr
⇒ **Expr Op Expr**
⇒ **Expr Op** `(`**Expr**`)`
⇒ **Expr Op** `(`**Expr Op Expr**`)`
⇒ **Expr** `×` `(`**Expr Op Expr**`)`
⇒ `int × (`**Expr Op Expr**`)`
⇒ `int × (int` **Op Expr**`)`
⇒ `int × (int` **Op** `int)`
⇒ `int × (int + int)`

- A sequence of zero or more steps where nonterminals are replaced by the right-hand side of a production is called a ***derivation***.
- If string $\boldsymbol{\alpha}$ derives string $\boldsymbol{\omega}$, we write $\boldsymbol{\alpha} \Rightarrow^{*} \boldsymbol{\omega}$.
- In the example on the left, we see that

Expr $\Rightarrow^{*}$ `int × (int + int)`.

Expr → `int` | **Expr Op Expr** | `(`**Expr**`)`
Op → `+` | `-` | `×` | `/`

The Language of a Grammar

- If G is a CFG with alphabet Σ and start symbol **S**, then the ***language of G*** is the set

$$\mathscr{L}(G) = \{ \boldsymbol{\omega} \in \Sigma^* \mid \mathbf{S} \Rightarrow^* \boldsymbol{\omega} \}$$

- That is, $\mathscr{L}(G)$ is the set of strings of terminals derivable from the start symbol.

If G is a CFG with alphabet Σ and start symbol **S**, then the ***language of G*** is the set

$$\mathscr{L}(G) = \{\ \omega \in \Sigma^* \mid \mathbf{S} \Rightarrow^* \omega\ \}$$

Consider the following CFG G over Σ = {**a**, **b**, **c**, **d**}:

Q → **Qa** | **dH**

H → **bHb** | **c**

Which of the following strings are in $\mathscr{L}(G)$?

dca

dc

cad

bcb

dHaa

PollEv.com/cs103spr26

Context-Free Languages

- A language L is called a ***context-free language*** (or CFL) if there is a CFG G such that $L = \mathscr{L}(G)$.

- Questions:
  - How are context-free and regular languages related?
  - How do we design context-free grammars for context-free languages?

Context-Free Languages

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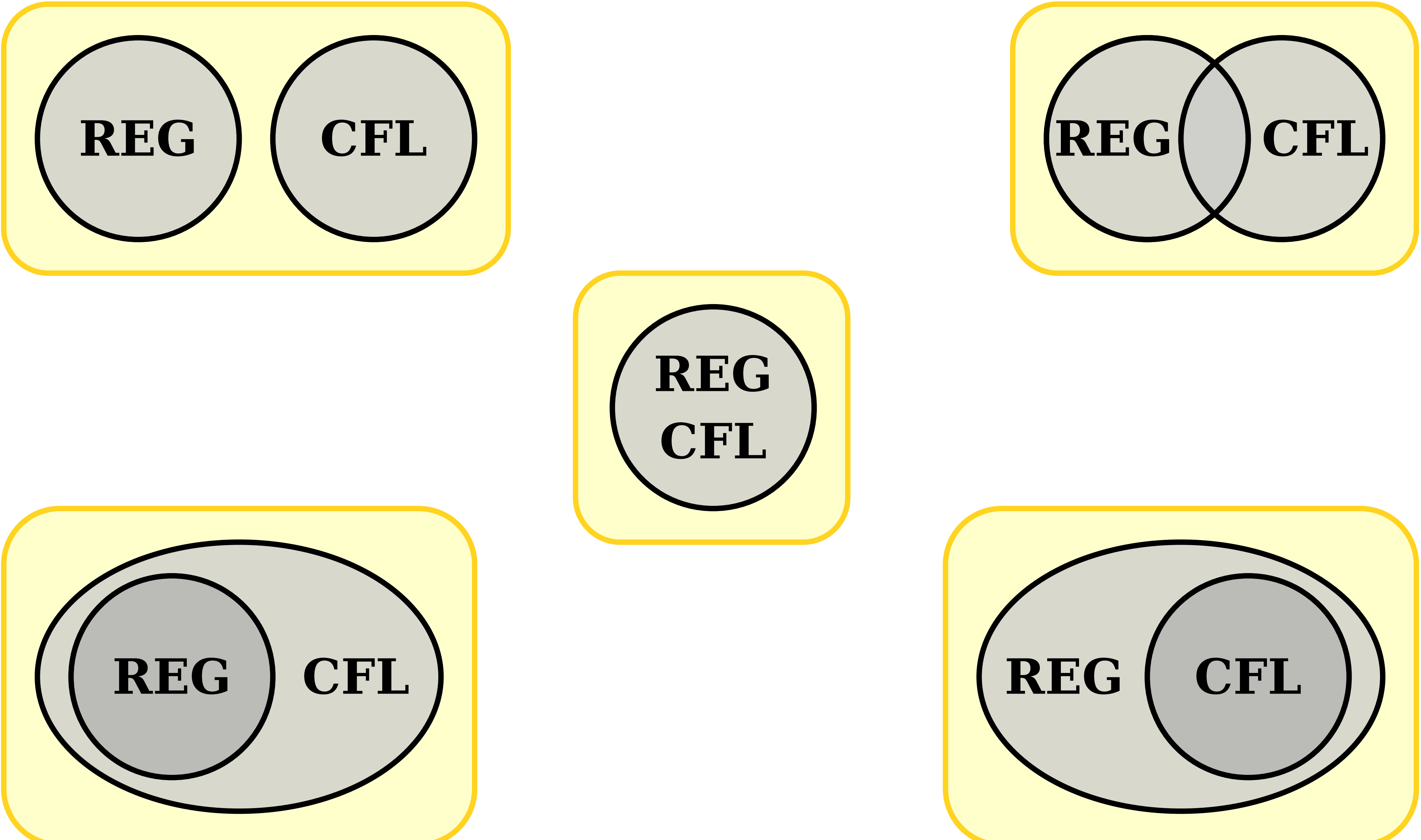
Questions:

- How are context-free and regular languages related?

  How do we design context-free grammars for context-free languages?

Five Possibilities



CFGs and Regular Expressions

- CFGs consist purely of production rules of the form **A** → ***ω***. They do not have the regular expression operators * or ∪.
- You can use the symbols * and ∪ if you'd like in a CFG, but they just stand for themselves.
- Consider this CFG G:

$$\mathbf{S} \rightarrow \mathbf{a*b}$$

- Here, $\mathscr{L}(G) = \{$**a*b**$\}$ and has cardinality one. That is, $\mathscr{L}(G) \neq \{\ \mathbf{a}^n\mathbf{b} \mid n \in \mathbb{N}\ \}$.

CFGs and Regular Expressions

- ***Theorem:*** Every regular language is context-free.
- ***Proof idea:*** Show how to convert an arbitrary regular expression into a context-free grammar.

a (b ∪ ε) c

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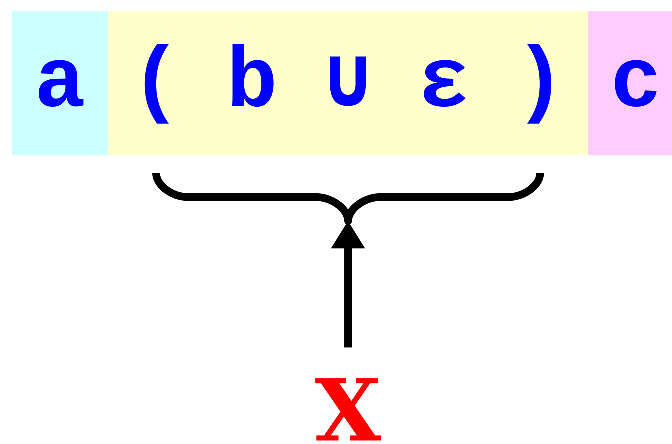

CFGs and Regular Expressions

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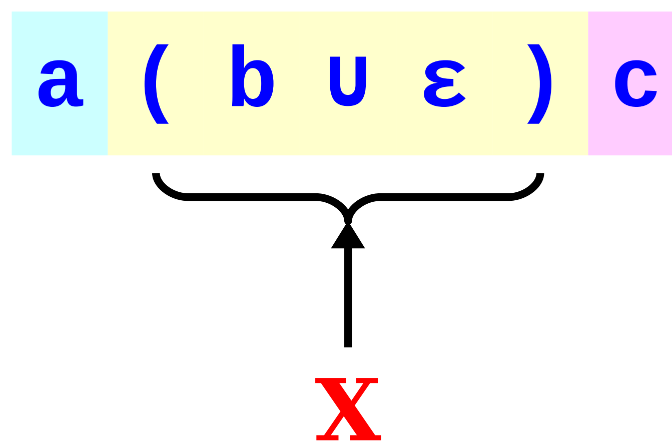
S → **aXc**



CFGs and Regular Expressions

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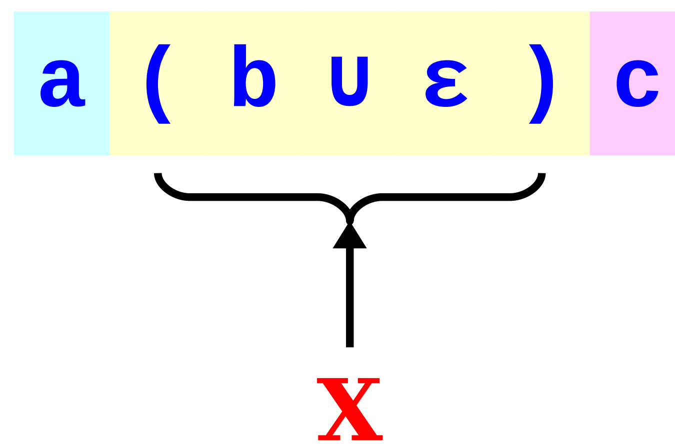
S → **aXc**

X → **b** | ε



CFGs and Regular Expressions

- ***Theorem:*** Every regular language is context-free.
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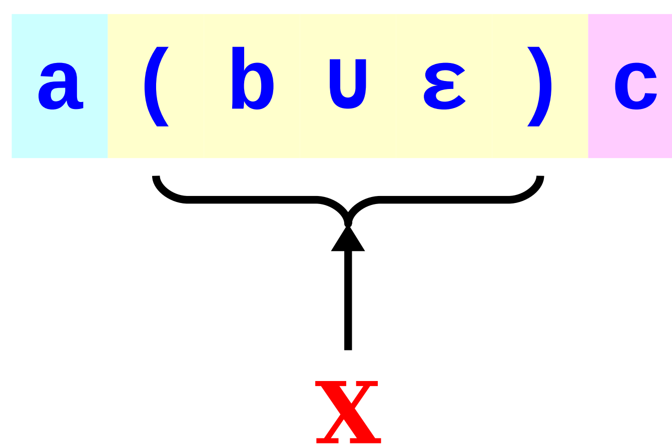
S → **aXc**

X → **b** | ε

It's totally fine for a production to replace a nonterminal with the empty string.



CFGs and Regular Expressions

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(a ∪ b)² c *

CFGs and Regular Expressions

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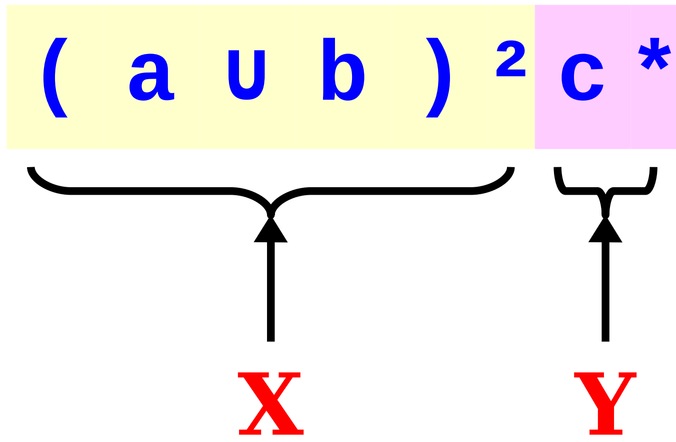

CFGs and Regular Expressions

- ***Theorem:*** Every regular language is context-free.
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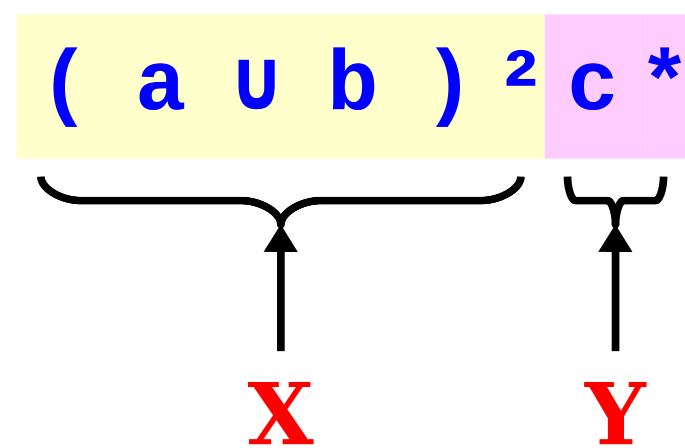
S → **XY**



CFGs and Regular Expressions

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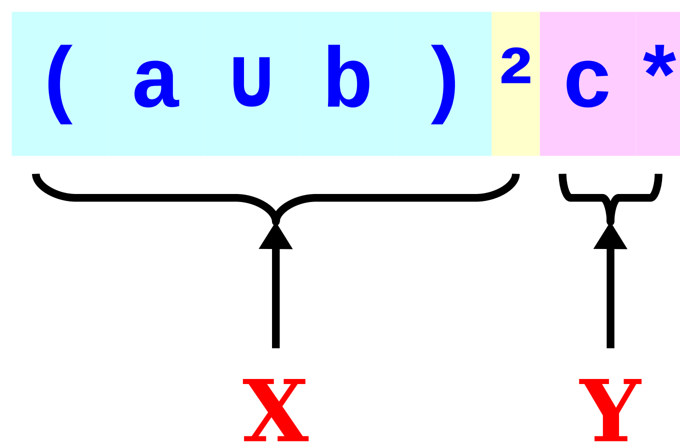

CFGs and Regular Expressions

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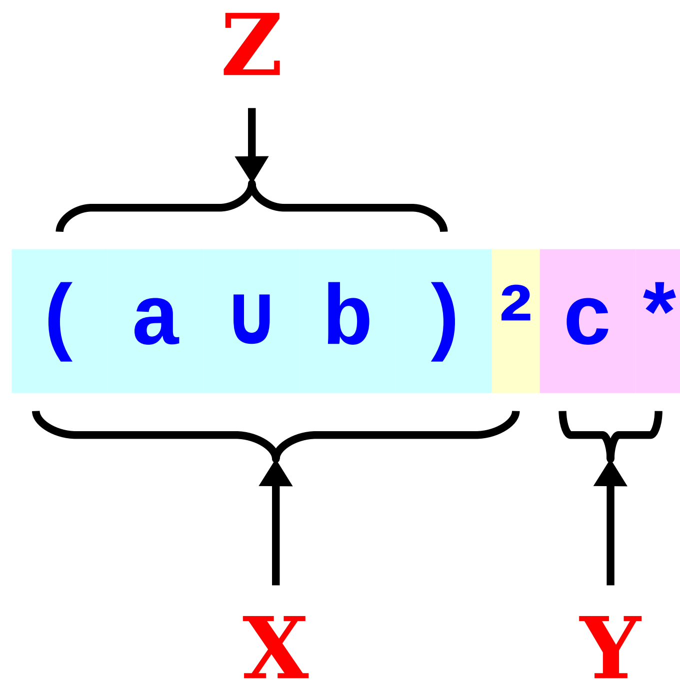
S → **XY**

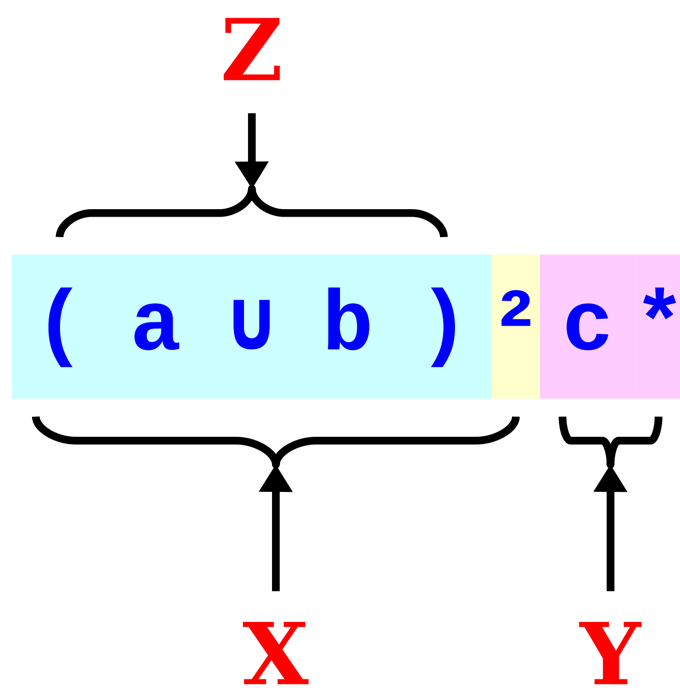


CFGs and Regular Expressions

- ***Theorem:*** Every regular language is context-free.
- ***Proof idea:*** Show how to convert an arbitrary regular expression into a context-free grammar.

S → **XY**

X → **ZZ**



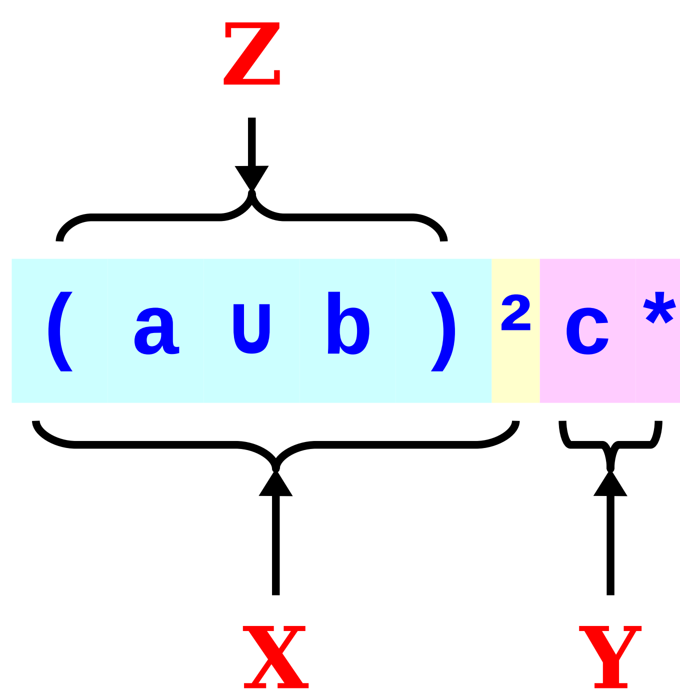
CFGs and Regular Expressions

- ***Theorem:*** Every regular language is context-free.
- ***Proof idea:*** Show how to convert an arbitrary regular expression into a context-free grammar.

S → **XY**

X → **ZZ**

Z → **a** | **b**



CFGs and Regular Expressions

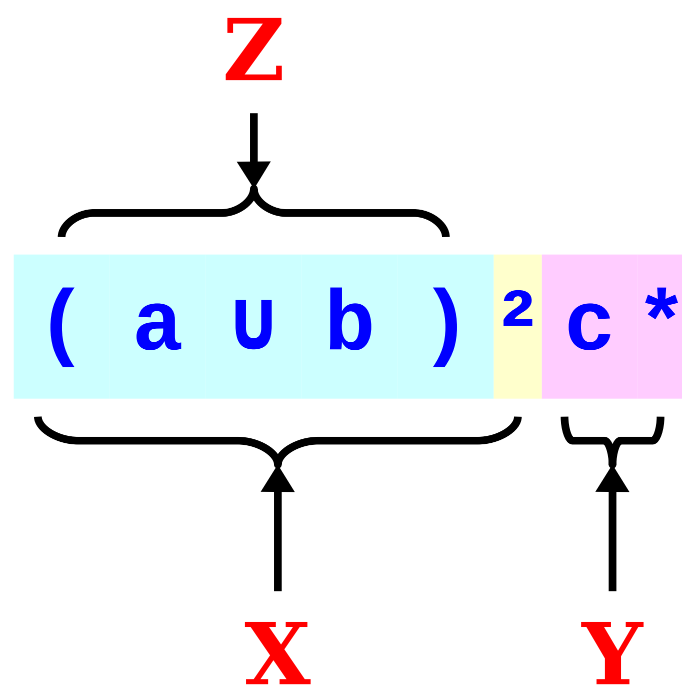
- ***Theorem:*** Every regular language is context-free.
- ***Proof idea:*** Show how to convert an arbitrary regular expression into a context-free grammar.

S → **XY**

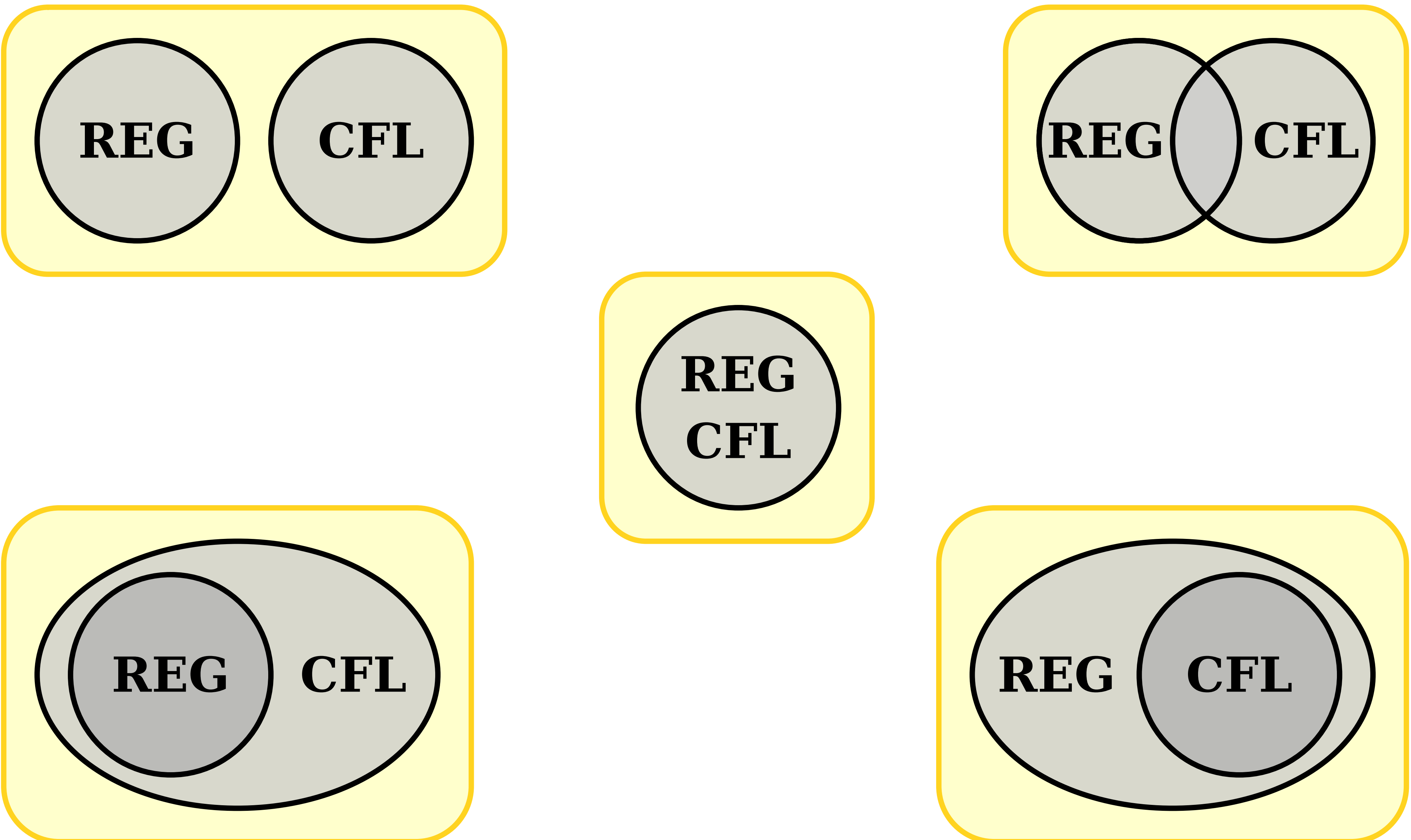
X → **ZZ**

Z → **a** | **b**

Y → **cY** | ε



Two ~~Five~~ Possibilities



The Language of a Grammar

- Consider the following CFG *G*:

$$\mathbf{S} \rightarrow \mathtt{a}\mathbf{S}\mathtt{b} \mid \varepsilon$$

- What strings can this grammar generate?

The Language of a Grammar

- Consider the following CFG *G*:

$$S \rightarrow aSb \mid \varepsilon$$

- What strings can this grammar generate?

S

The Language of a Grammar

- Consider the following CFG *G*:

$$S \rightarrow aSb \mid \varepsilon$$

- What strings can this grammar generate?

a	S	b

The Language of a Grammar

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a	S	b

The Language of a Grammar

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a	**a**	**S**	**b**	**b**

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a	a	S	b	b

The Language of a Grammar

- Consider the following CFG *G*:

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- What strings can this grammar generate?

a	a	a	S	b	b	b

The Language of a Grammar

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a	a	a		S		b	b	b

The Language of a Grammar

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a	a	a	a	S	b	b	b	b

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a	a	a	a		b	b	b	b

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$$S \rightarrow \mathtt{a}S\mathtt{b} \mid \varepsilon$$

- What strings can this generate?

a	a	a	a	b	b	b	b

The Language of a Grammar

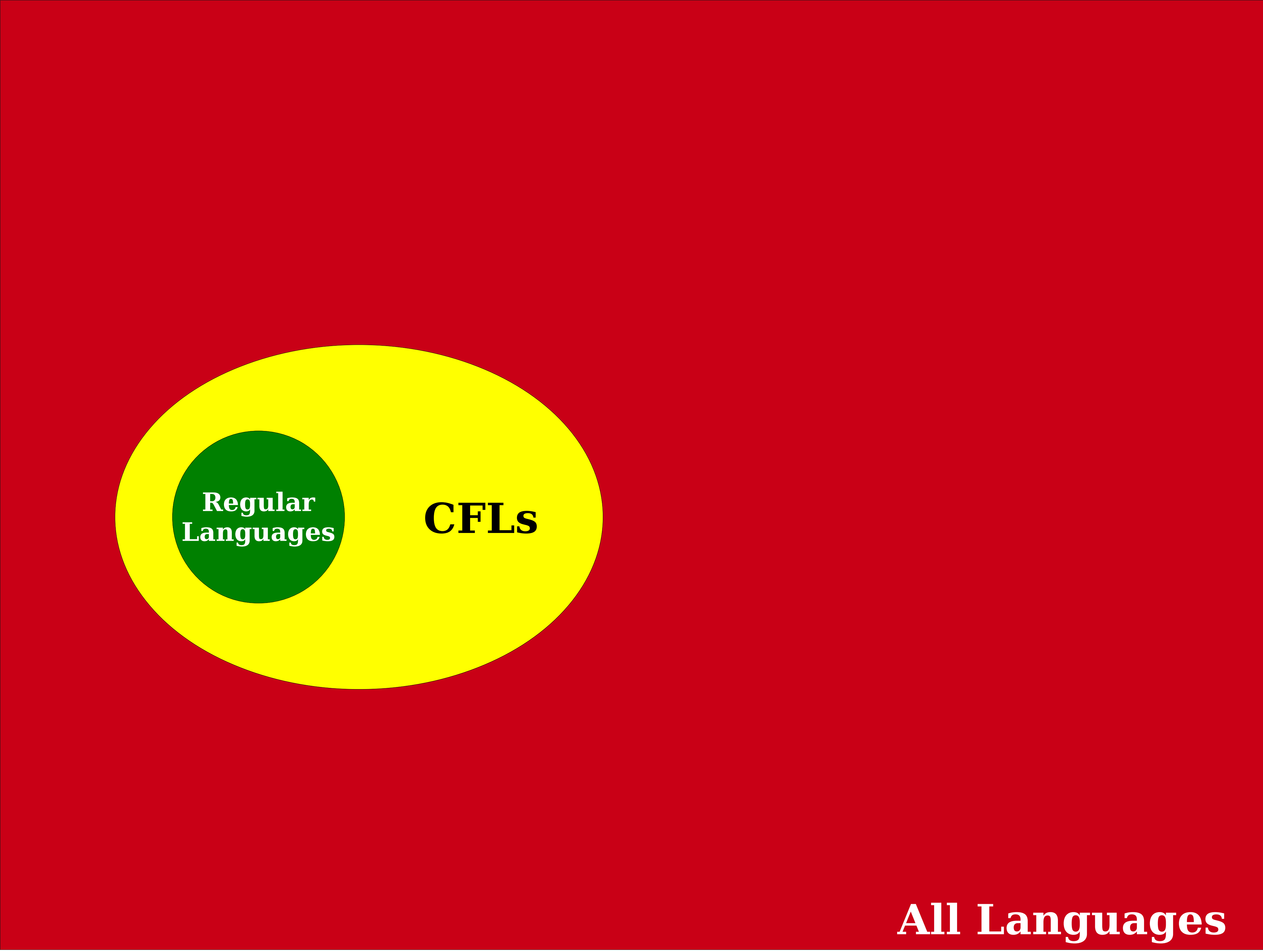
- Consider the following CFG G:

$$\mathbf{S} \rightarrow \mathtt{a}\mathbf{S}\mathtt{b} \mid \varepsilon$$

- What strings can this generate?

a	a	a	a	b	b	b	b

$$\mathscr{L}(G) = \{ \mathtt{a}^n\mathtt{b}^n \mid n \in \mathbb{N} \}$$


Regular Languages
CFLs
All Languages

Why the Extra Power?

- Why do CFGs have more power than regular expressions?
- ***Intuition:*** Derivations of strings have unbounded “memory.”

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S → **aSb** | **ε**

S

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a	a	a	S	b	b	b

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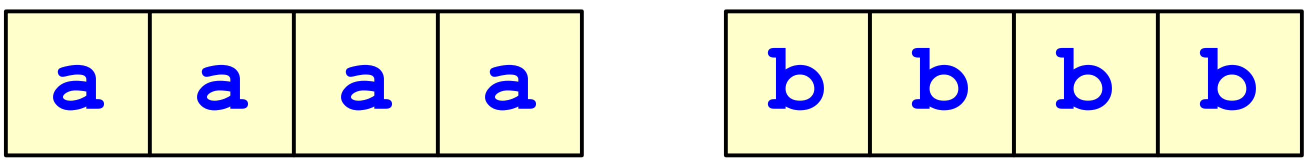

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Designing CFGs

- Like designing DFAs, NFAs, and regular expressions, designing CFGs is a craft.
- When thinking about CFGs:
  - ***Think recursively:*** Build up bigger structures from smaller ones.
  - ***Have a construction plan:*** Know in what order you will build up the string.
  - ***Store information in nonterminals:*** Have each nonterminal correspond to some useful piece of information.
- Check our online "Guide to CFGs" for more information about CFG design.
- We'll hit the highlights in the rest of this lecture.

Designing CFGs

- Let Σ = {**a**, **b**} and let $L = \{w \in \Sigma^* \mid w$ is a palindrome $\}$
- We can design a CFG for L by thinking inductively:
  - Base case: ε, **a**, and **b** are palindromes.
  - If ω is a palindrome, then **a**ω**a** and **b**ω**b** are palindromes.
  - No other strings are palindromes.

S → ε | a | b | aSa | bSb

Designing CFGs

- Let Σ = {**{**, **}**} and let *L* = {*w* ∈ Σ* | *w* is a string of balanced braces }
- Some sample strings in *L*:

{{{}}}

{{}}{}

{{}{}}{{}{}}

{{{{}}}{{}}}}

ε

{}{}

Designing CFGs

- Let Σ = {**{**, **}**} and let $L = \{ w \in \Sigma^* \mid w$ is a string of balanced braces }
- Let's think about this recursively.
  - Base case: the empty string is a string of balanced braces.
  - Recursive step: Look at the closing brace that matches the first open brace.

{{{}{{}}}{{}}}{{}}{{{}}}

Designing CFGs

- Let $\Sigma = \{\{, \}\}$ and let $L = \{w \in \Sigma^* \mid w$ is a string of balanced braces $\}$
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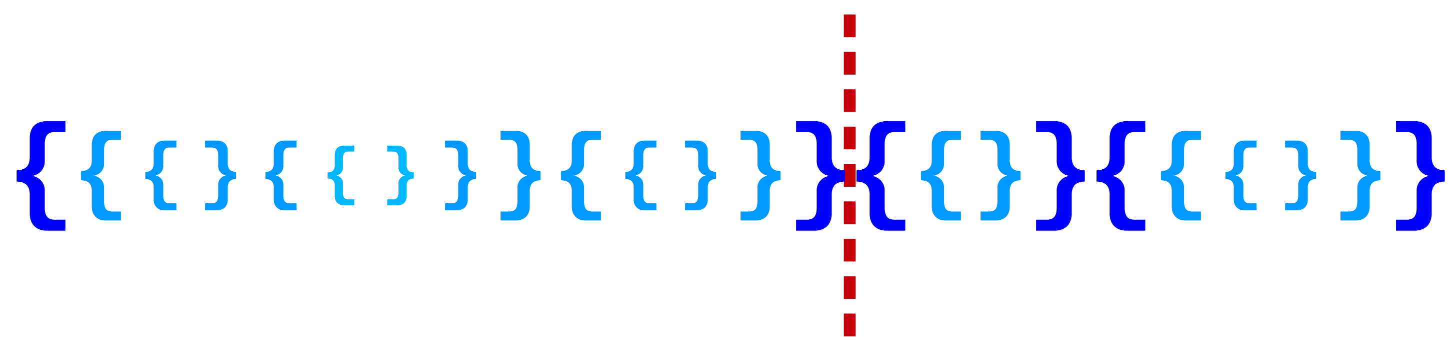

Designing CFGs

- Let Σ = {**{**, **}**} and let L = {$w \in \Sigma^*$ | w is a string of balanced braces }
- Let's think about this recursively.
  - Base case: the empty string is a string of balanced braces.
  - Recursive step: Look at the closing brace that matches the first open brace.

{{}{{}}}{{}} | {{}}{{{}}}

Designing CFGs

- Let $\Sigma = \{ \mathbf{\{}, \mathbf{\}} \}$ and let $L = \{ w \in \Sigma^* \mid w \text{ is a string of balanced braces } \}$
- Let's think about this recursively.
  - Base case: the empty string is a string of balanced braces.
  - Recursive step: Look at the closing brace that matches the first open brace. Removing the first brace and the matching brace forms two new strings of balanced braces.

$$\mathbf{S} \rightarrow \mathbf{\{S\}S} \mid \boldsymbol{\varepsilon}$$

Designing CFGs

- Let $\Sigma = \{\mathbf{a}, \mathbf{b}\}$ and let $L = \{ w \in \Sigma^* \mid w$ has the same number of **a**'s and **b**'s $\}$

Which of these CFGs have language L?

S → **aSb** | **bSa** | **ε**

S → **abS** | **baS** | **ε**

S → **abSba** | **baSab** | **ε**

S → **SbaS** | **SabS** | **ε**

Designing CF

PollEv.com/cs103spr26

- Let Σ = {**a**, **b**} and let L = {
has the same number of **a**'s

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S → aSb | bSa | ε	**S → abS | baS | ε**
S → abSba | baSab | ε	**S → SbaS | SabS | ε**

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S → **aSb** | **bSa** | **ε**	**S** → **abS** | **baS** | **ε**
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- Let $\Sigma = \{\mathbf{a}, \mathbf{b}\}$ and let $L = \{w \in \Sigma^* \mid w$ has the same number of **a**'s and **b**'s $\}$

Which of these CFGs have language L?

S → aSb | bSa | ε

S → abS | baS | ε

S → abSba | baSab | ε

S → SbaS | SabS | ε

Designing CFGs: A Caveat

- When designing a CFG for a language, make sure that it
  - generates all the strings in the language and
  - never generates a string outside the language.
- The first of these can be tricky – make sure to test your grammars!

CFG Caveats II

- Is the following grammar a CFG for the language $\{ \mathbf{a}^n\mathbf{b}^n \mid n \in \mathbb{N} \}$?

$$\mathbf{S} \rightarrow \mathbf{aSb}$$

- What strings in {**a**, **b**}* can you derive?
  - Answer: ***None!***
- What is the language of the grammar?
  - Answer: **Ø**
- When designing CFGs, make sure your recursion actually terminates!

Designing CFGs

- When designing CFGs, remember that each nonterminal can be expanded out independently of the others.
- Let $\Sigma = \{\mathbf{a}, \stackrel{?}{=}\}$ and let $L = \{\mathbf{a}^n \stackrel{?}{=} \mathbf{a}^n \mid n \in \mathbb{N}\}$.
- Is the following a CFG for L?

$$\mathbf{S} \rightarrow \mathbf{X} \stackrel{?}{=} \mathbf{X}$$

$$\mathbf{X} \rightarrow \mathbf{aX} \mid \varepsilon$$

$$\begin{aligned}
& \mathbf{S} \\
\Rightarrow\ & \mathbf{X} \stackrel{?}{=} \mathbf{X} \\
\Rightarrow\ & \mathbf{aX} \stackrel{?}{=} \mathbf{X} \\
\Rightarrow\ & \mathbf{aaX} \stackrel{?}{=} \mathbf{X} \\
\Rightarrow\ & \mathbf{aa} \stackrel{?}{=} \mathbf{X} \\
\Rightarrow\ & \mathbf{aa} \stackrel{?}{=} \mathbf{aX} \\
\Rightarrow\ & \mathbf{aa} \stackrel{?}{=} \mathbf{a}
\end{aligned}$$

Finding a Build Order

- Let $\Sigma = \{\mathbf{a}, \stackrel{?}{=}\}$ and let $L = \{\mathbf{a}^n\stackrel{?}{=}\mathbf{a}^n \mid n \in \mathbb{N}\}$.
- To build a CFG for L, we need to be more clever with how we construct the string.
  - If we build the strings of **a**'s independently of one another, then we can't enforce that they have the same length.
  - ***Idea:*** Build both strings of **a**'s at the same time.
- Here's one possible gramm[...] that idea:

$$\mathbf{S} \rightarrow \stackrel{?}{=} \mid \mathbf{aSa}$$

$$\begin{aligned} & \mathbf{S} \\ \Rightarrow\ & \mathbf{aSa} \\ \Rightarrow\ & \mathbf{aaSaa} \\ \Rightarrow\ & \mathbf{aaaSaaa} \\ \Rightarrow\ & \mathbf{aaa}\stackrel{?}{=}\mathbf{aaa} \end{aligned}$$

Summary of CFG Design Tips

- Look for recursive structures where they exist: they can help guide you toward a solution.
- Keep the build order in mind – often, you'll build two totally different parts of the string concurrently.
  - Usually, those parts are built in opposite directions: one's built left-to-right, the other right-to-left.
- Use different nonterminals to represent different structures.

Applications of Context-Free Grammars

CFGs for Programming Languages

```
BLOCK  →  STMT
       |  { STMTS }

STMTS  →  ε
       |  STMT STMTS

STMT   →  EXPR;
       |  if (EXPR) BLOCK
       |  while (EXPR) BLOCK
       |  do BLOCK while (EXPR);
       |  BLOCK
       |  …

EXPR   →  identifier
       |  constant
       |  EXPR + EXPR
       |  EXPR – EXPR
       |  EXPR * EXPR
       |  …
```

Grammars in Compilers

- One of the key steps in a compiler is figuring out what a program "means."
- This is usually done by defining a grammar showing the high-level structure of a programming language.
- There are certain classes of grammars (LL(1) grammars, LR(1) grammars, LALR(1) grammars, etc.) for which it's easy to figure out how a particular string was derived.
- Tools like `yacc` or `bison` automatically generate parsers from these grammars.
- Curious to learn more? ***Take CS143!***

Natural Language Processing

- By building context-free grammars for actual languages and applying statistical inference, it's possible for a computer to recover the likely meaning of a sentence.
  - In fact, CFGs were first called ***phrase-structure grammars*** and were introduced by Noam Chomsky in his seminal work *Syntactic Structures*.
  - They were then adapted for use in the context of programming languages, where they were called ***Backus-Naur forms***.
- The **Stanford Parser** project is one place to look for an example of this.
- Want to learn more? Take CS124 or CS224N!

Next Time

Turing Machines

- What does a computer with unbounded memory look like?
- How would you program it?