Regular Expressions
Recap from Last Time
Regular Languages

• A language $L$ is a regular language if there is a DFA $D$ such that $\mathcal{L}(D) = L$.

• **Theorem:** The following are equivalent:
  • $L$ is a regular language.
  • There is a DFA for $L$.
  • There is an NFA for $L$. 
Language Concatenation

- If \( w \in \Sigma^* \) and \( x \in \Sigma^* \), then \( wx \) is the **concatenation** of \( w \) and \( x \).
- If \( L_1 \) and \( L_2 \) are languages over \( \Sigma \), the **concatenation** of \( L_1 \) and \( L_2 \) is the language \( L_1L_2 \) defined as
  \[
  L_1L_2 = \{ \, wx \mid w \in L_1 \text{ and } x \in L_2 \, \}
  \]
- Example: if \( L_1 = \{ \text{a, ba, bb} \} \) and \( L_2 = \{ \text{aa, bb} \} \), then
  \[
  L_1L_2 = \{ \text{aaa, abb, baaa, babb, bbao, bbbb} \}
  \]
Lots and Lots of Concatenation

• Consider the language \( L = \{ \text{aa, b} \} \)

• \( LL \) is the set of strings formed by concatenating pairs of strings in \( L \).
  \[
  \{ \text{aaaa, aab, baa, bb} \}
  \]

• \( LLL \) is the set of strings formed by concatenating triples of strings in \( L \).
  \[
  \{ \text{aaaaaa, aaaaab, aabaa, aabb, baaaa, baab, bbaa, bbb} \}
  \]

• \( LLLL \) is the set of strings formed by concatenating quadruples of strings in \( L \).
  \[
  \{ \text{aaaaaaaa, aaaaaab, aaaaaabaa, aaaaabb, aabaaaaa, aabaab, aabbaaa, aabbaab, aabbb, baaaaaa, baaaaab, baabaa, baabb, bbaaaa, bbaab, bbbaa, bbbb} \}
  \]
Language Exponentiation

• We can define what it means to “exponentiate” a language as follows:

  • $L^0 = \{ \varepsilon \}$
    • The set containing just the empty string.
    • Idea: Any string formed by concatenating zero strings together is the empty string.

  • $L^{n+1} = LL^n$
    • Idea: Concatenating $(n+1)$ strings together works by concatenating $n$ strings, then concatenating one more.

• **Question:** Why define $L^0 = \{ \varepsilon \}$?
The Kleene Closure

● An important operation on languages is the **Kleene Closure**, which is defined as

\[ L^* = \{ w \in \Sigma^* \mid \exists n \in \mathbb{N}. w \in L^n \} \]

● Mathematically:

\[ w \in L^* \iff \exists n \in \mathbb{N}. w \in L^n \]

● Intuitively, all possible ways of concatenating zero or more strings in \( L \) together, possibly with repetition.
The Kleene Closure

If \( L = \{ \text{a, bb} \} \), then \( L^* = \{
\epsilon,
\text{a, bb},
\text{aa, abb, bba, bbb},
\text{aaa, aabb, abba, abbbb, bbaa, bbabb, bbbba, bbbbbbb,}
\ldots
\}

Think of \( L^* \) as the set of strings you can make if you have a collection of stamps – one for each string in \( L \) – and you form every possible string that can be made from those stamps.
Closure Properties

- **Theorem:** If $L_1$ and $L_2$ are regular languages over an alphabet $\Sigma$, then so are the following languages:
  - $\overline{L_1}$
  - $L_1 \cup L_2$
  - $L_1 \cap L_2$
  - $L_1L_2$
  - $L_1^*$

- These properties are called **closure properties of the regular languages.**
New Stuff!
Another View of Regular Languages
Rethinking Regular Languages

• We currently have several tools for showing a language \( L \) is regular:
  • Construct a DFA for \( L \).
  • Construct an NFA for \( L \).
  • Combine several simpler regular languages together via closure properties to form \( L \).

• We have not spoken much of this last idea.
Constructing Regular Languages

- **Idea:** Build up all regular languages as follows:
  - Start with a small set of simple languages we already know to be regular.
  - Using closure properties, combine these simple languages together to form more elaborate languages.
- *A bottom-up approach to the regular languages.*
Constructing Regular Languages

• **Idea:** Build up all regular languages as follows:
  • Start with a small set of simple languages we already know to be regular.
  • Using closure properties, combine these simple languages to form more elaborate languages.
  • A bottom-up approach to the regular languages.
Regular Expressions

- **Regular expressions** are a way of describing a language via a string representation.
- They’re used extensively in software systems for string processing and as the basis for tools like `grep` and `flex`.
- Conceptually, regular expressions are strings describing how to assemble a larger language out of smaller pieces.
Atomic Regular Expressions

- The regular expressions begin with three simple building blocks.
- The symbol $\emptyset$ is a regular expression that represents the empty language $\emptyset$.
- For any $a \in \Sigma$, the symbol $a$ is a regular expression for the language $\{a\}$.
- The symbol $\epsilon$ is a regular expression that represents the language $\{\epsilon\}$.

  - Remember: $\{\epsilon\} \neq \emptyset$!
  - Remember: $\{\epsilon\} \neq \epsilon$!
Compound Regular Expressions

• If $R_1$ and $R_2$ are regular expressions, $R_1R_2$ is a regular expression for the *concatenation* of the languages of $R_1$ and $R_2$.

• If $R_1$ and $R_2$ are regular expressions, $R_1 \cup R_2$ is a regular expression for the *union* of the languages of $R_1$ and $R_2$.

• If $R$ is a regular expression, $R^*$ is a regular expression for the *Kleene closure* of the language of $R$.

• If $R$ is a regular expression, $(R)$ is a regular expression with the same meaning as $R$. 
Operator Precedence

• Here’s the operator precedence for regular expressions, from highest to lowest:
  
  - $(R)$
  - $R^*$
  - $R_1R_2$
  - $R_1 \cup R_2$

Consider the regular expression $ab^*cUd$
How many of the strings below are in the language described by this regular expression?

- ababca
- abd
- ac
- abcd

Answer at PollEv.com/cs103 or text CS103 to 22333 once to join, then a number.
Regular Expression Examples

• The regular expression \texttt{trick} \cup \texttt{treat} represents the regular language \{ \texttt{trick}, \texttt{treat} \}.

• The regular expression \texttt{booo*} represents the regular language \{ \texttt{boo}, \texttt{booo}, \texttt{boooo}, \ldots \}.

• The regular expression \texttt{candy!(candy!)*} represents the regular language \{ \texttt{candy!}, \texttt{candy!candy!}, \texttt{candy!candy!candy!}, \ldots \}. 
The *language of a regular expression* is the language described by that regular expression.

Formally:

- $\mathcal{L}(\varepsilon) = \{\varepsilon\}$
- $\mathcal{L}(\emptyset) = \emptyset$
- $\mathcal{L}(a) = \{a\}$
- $\mathcal{L}(R_1 R_2) = \mathcal{L}(R_1) \cdot \mathcal{L}(R_2)$
- $\mathcal{L}(R_1 \cup R_2) = \mathcal{L}(R_1) \cup \mathcal{L}(R_2)$
- $\mathcal{L}(R^*) = \mathcal{L}(R)^*$
- $\mathcal{L}(\langle R \rangle) = \mathcal{L}(R)$

Worthwhile activity: Apply this recursive definition to

\[ a(b\cup c)((d)) \]

and see what you get.
Designing Regular Expressions

- Let $\Sigma = \{a, b\}$.
- Let $L = \{ w \in \Sigma^* \mid w \text{ contains } aa \text{ as a substring} \}$. 
Designing Regular Expressions

- Let $\Sigma = \{a, b\}$.
- Let $L = \{ w \in \Sigma^* | w$ contains $aa$ as a substring $\}$.

$(a \cup b)^*aa(a \cup b)^*$
Designing Regular Expressions

• Let $\Sigma = \{a, b\}$.

• Let $L = \{ w \in \Sigma^* \mid w$ contains $aa$ as a substring $\}$.

  $(a \cup b)^*aa(a \cup b)^*$
Designing Regular Expressions

- Let $\Sigma = \{a, b\}$.
- Let $L = \{ w \in \Sigma^* \mid w$ contains $aa$ as a substring $\}$. 

$$(a \cup b)^*aa(a \cup b)^*$$

$bbabbbbaaabab$

$aaaa$

$bbbbbbabbbbaabbbbb$
Designing Regular Expressions

• Let $\Sigma = \{a, b\}$.

• Let $L = \{ w \in \Sigma^* \mid w$ contains $aa$ as a substring $\}$. 

  \[(a \cup b)^*aa(a \cup b)^*\]

  
  \[
  \begin{align*}
  &bbabbbbaaabab \\
  &aaaa \\
  &bbbbbbabbbbbbaabbbbbbb
  \end{align*}
  \]
Designing Regular Expressions

- Let $\Sigma = \{a, b\}$.
- Let $L = \{ w \in \Sigma^* \mid w \text{ contains } aa \text{ as a substring } \}$. 

$\Sigma^*aa\Sigma^*$

- $bbabbbaaabab$
- $aaaa$
- $bbbbbabbbbaaabbbbb$
Designing Regular Expressions

• Let $\Sigma = \{a, b\}$.
• Let $L = \{w \in \Sigma^* \mid |w| = 4\}$. 
Designing Regular Expressions

Let $\Sigma = \{a, b\}$.
Let $L = \{ w \in \Sigma^* \mid |w| = 4 \}.$

The length of a string $w$ is denoted $|w|$. 
Designing Regular Expressions

• Let $\Sigma = \{ a, b \}$.
• Let $L = \{ w \in \Sigma^* \mid |w| = 4 \}$. 
Designing Regular Expressions

• Let $\Sigma = \{a, b\}$.
• Let $L = \{ w \in \Sigma^* \mid |w| = 4 \}$. 

ΣΣΣΣ
Designing Regular Expressions

Let $\Sigma = \{a, b\}$.

Let $L = \{w \in \Sigma^* \mid |w| = 4\}$. 
Designing Regular Expressions

• Let $\Sigma = \{ a, b \}$.
• Let $L = \{ w \in \Sigma^* \mid |w| = 4 \}$.
Designing Regular Expressions

- Let $\Sigma = \{a, b\}$.
- Let $L = \{ w \in \Sigma^* \mid |w| = 4 \}$. 
Designing Regular Expressions

- Let $\Sigma = \{a, b\}$.
- Let $L = \{ w \in \Sigma^* \mid |w| = 4 \}$. 

$\Sigma^4$

- aaaa
- baba
- bbbb
- baaa
Designing Regular Expressions

• Let $\Sigma = \{a, b\}$.
• Let $L = \{ w \in \Sigma^* \mid |w| = 4 \}$. 

$\Sigma^4$

aaaa
baba
bbbb
baaa
Designing Regular Expressions

- Let $\Sigma = \{a, b\}$.
- Let $L = \{ w \in \Sigma^* \mid w \text{ contains at most one } a \}$.

Which of the following is a regular expression for $L$?

A. $\Sigma^*a\Sigma^*$
B. $b^*ab^* \cup b^*$
C. $b^*(a \cup \varepsilon)b^*$
D. $b^*a*b^* \cup b^*$
E. $b^*(a^* \cup \varepsilon)b^*$
F. None of the above, or two or more of the above.

Answer at PollEv.com/cs103 or text CS103 to 22333 once to join, then A, B, C, D, E, or F.
Designing Regular Expressions

- Let $\Sigma = \{a, b\}$.
- Let $L = \{ w \in \Sigma^* \mid w \text{ contains at most one } a \}$.

$b^* (a \cup \varepsilon) b^*$
Designing Regular Expressions

- Let $\Sigma = \{a, b\}$.
- Let $L = \{ w \in \Sigma^* | w$ contains at most one $a \}$. 

$$b^*(a \cup \varepsilon)b^*$$
Designing Regular Expressions

• Let $\Sigma = \{a, b\}$.

• Let $L = \{ w \in \Sigma^* \mid w \text{ contains at most one } a \}$. 

\[
\text{b*}(a \cup \varepsilon)b^*
\]

\[
\text{bbbbabbb}
\]

\[
\text{bbbbbb}
\]

\[
\text{abbb}
\]

\[
\text{a}
\]
Designing Regular Expressions

- Let $\Sigma = \{a, b\}$.
- Let $L = \{ w \in \Sigma^* \mid w$ contains at most one $a \}$. 

\[
b^* (a \cup \varepsilon) b^* 
\]

Examples:
- $bbbbaabbb$
- $bbbbbbbb$
- $aabbb$
- $a$
Designing Regular Expressions

• Let $\Sigma = \{a, b\}$.

• Let $L = \{ w \in \Sigma^* \mid w \text{ contains at most one } a \}$. 

\[ b^*a?b^* \]

\[
\begin{align*}
&\quad \text{bbbbabbb} \\
&\quad \text{bbbbbbb} \\
&\quad \text{abbb} \\
&\quad a
\end{align*}
\]
A More Elaborate Design

• Let $\Sigma = \{ a, ., @ \}$, where $a$ represents “some letter.”

• Let's make a regex for email addresses.
A More Elaborate Design

• Let $\Sigma = \{ a, ., @ \}$, where $a$ represents “some letter.”
• Let's make a regex for email addresses.

cs103@cs.stanford.edu
first.middle.last@mail.site.org
dot.at@dot.com
A More Elaborate Design

- Let $\Sigma = \{ a, ., @ \}$, where $a$ represents “some letter.”
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A More Elaborate Design

- Let $\Sigma = \{a, ., @\}$, where $a$ represents “some letter.”
- Let's make a regex for email addresses.

```
aa*
```

```
cs103@cs.stanford.edu
first.middle.last@mail.site.org
dot.at@dot.com
```
A More Elaborate Design

• Let $\Sigma = \{ \text{a, ., @} \}$, where $\text{a}$ represents “some letter.”

• Let's make a regex for email addresses.

  `aa*`

  `cs103@cs.stanford.edu`
  `first.middle.last@mail.site.org`
  `dot.at@dot.com`
A More Elaborate Design

• Let $\Sigma = \{ \text{a, ., @} \}$, where $\text{a}$ represents “some letter.”

• Let's make a regex for email addresses.

  \[
  \text{aa* (.aa*)*}
  \]

  \begin{align*}
  \text{cs103@cs.stanford.edu} \\
  \text{first.middle.last@mail.site.org} \\
  \text{dot.at@dot.com}
  \end{align*}
A More Elaborate Design

• Let $\Sigma = \{ a, ., @ \}$, where $a$ represents “some letter.”

• Let's make a regex for email addresses.

\[
\text{aa* (.aa*)*}
\]

- cs103@cs.stanford.edu
- first.middle.last@mail.site.org
- dot.at@dot.com
A More Elaborate Design

• Let $\Sigma = \{a, ., @\}$, where $a$ represents “some letter.”
• Let's make a regex for email addresses.

```
  aa* (.aa*)* @
```

```
cs103@cs.stanford.edu
first.middle.last@mail.site.org
dot.at@dot.com
```
A More Elaborate Design

• Let $\Sigma = \{ a, ., @ \}$, where $a$ represents "some letter."

• Let's make a regex for email addresses.

$$aa* (.aa*)* @$$

$\text{cs103@cs.stanford.edu}$
$\text{first.middle.last@mail.site.org}$
$\text{dot.at@dot.com}$
A More Elaborate Design

• Let $\Sigma = \{a, ., @\}$, where a represents “some letter.”

• Let's make a regex for email addresses.

\[
\text{aa* (.aa*)* @ aa*.aa*}
\]

\[
\text{cs103@cs.stanford.edu}
\]
\[
\text{first.middle.last@mail.site.org}
\]
\[
\text{dot.at@dot.com}
\]
A More Elaborate Design

• Let $\Sigma = \{a, ., @\}$, where $a$ represents “some letter.”

• Let's make a regex for email addresses.

  \[
  aa* (.aa*)* @ aa*.aa*
  \]

  cs103@cs.stanford.edu
  first.middle.last@mail.site.org
  dot.at@dot.com
A More Elaborate Design

- Let $\Sigma = \{ a, ., @ \}$, where $a$ represents "some letter."
- Let's make a regex for email addresses.

```
  aa* (.aa*)* @ aa*.aa* (.aa*)*
```

```
cs103@cs.stanford.edu
first.middle.last@mail.site.org
dot.at@dot.com
```
A More Elaborate Design

• Let $\Sigma = \{ a, ., @ \}$, where $a$ represents “some letter.”

• Let's make a regex for email addresses.

\[
\text{aa* (.aa*)* @ aa*.aa* (.aa*)*}
\]

\[
\text{cs103@cs.stanford.edu}
\]
\[
\text{first.middle.last@mail.site.org}
\]
\[
\text{dot.at@dot.com}
\]
A More Elaborate Design

- Let $\Sigma = \{ \text{a, ., @} \}$, where a represents "some letter."
- Let's make a regex for email addresses.

```
a+ (.aa*)* @ aa*.aa* (.aa*)*
```

cs103@cs.stanford.edu
first.middle.last@mail.site.org
dot.at@dot.com
A More Elaborate Design

• Let $\Sigma = \{ a, ., @ \}$, where $a$ represents “some letter.”

• Let's make a regex for email addresses.

$$a^+ (.aa*)* @ aa*.aa* (.aa*)*$$

$\text{cs103@cs.stanford.edu}$
$\text{first.middle.last@mail.site.org}$
$\text{dot.at@dot.com}$
A More Elaborate Design

• Let $\Sigma = \{ a, ., @ \}$, where $a$ represents “some letter.”

• Let's make a regex for email addresses.

$$a^+ (.a^+)* @ a^+.a^+ (\cdot.a^+)*$$

```plaintext
cs103@cs.stanford.edu
first.middle.last@mail.site.org
dot.at@dot.com
```
Let $\Sigma = \{ a, ., @ \}$, where $a$ represents “some letter.”

Let's make a regex for email addresses.

\[
a^+ \ (.a^+\)\* @ a^+ a^+ (.a^+\)\*
\]

- cs103@cs.stanford.edu
- first.middle.last@mail.site.org
- dot.at@dot.com
A More Elaborate Design

• Let $\Sigma = \{ a, ., @ \}$, where $a$ represents “some letter.”

• Let's make a regex for email addresses.

\[
a^+ (a^+)^* @ a^+ .a^+ (a^+)^*
\]

- cs103@cs.stanford.edu
- first.middle.last@mail.site.org
- dot.at@dot.com
A More Elaborate Design

- Let $\Sigma = \{ a, ., @ \}$, where $a$ represents “some letter.”
- Let's make a regex for email addresses.

Let's make a regular expression for email addresses:

```
  a+ (.a+)* @ a+ .a+ (.a+)*
```

Examples:
- `cs103@cs.stanford.edu`
- `first.middle.last@mail.site.org`
- `dot.at@dot.com`
A More Elaborate Design

• Let $\Sigma = \{ a, ., @ \}$, where $a$ represents “some letter.”

• Let's make a regex for email addresses.

$$a^+ (.a^+)* @ a^+ (.a^+)^+$$

- cs103@cs.stanford.edu
- first.middle.last@mail.site.org
- dot.at@dot.com
A More Elaborate Design

- Let $\Sigma = \{ a, ., @ \}$, where $a$ represents “some letter.”
- Let's make a regex for email addresses.

$$a^+ (a^*)^@ a^+ (a^+)^+$$

- $\text{cs103@cs.stanford.edu}$
- $\text{first.middle.last@mail.site.org}$
- $\text{dot.at@dot.com}$
A More Elaborate Design

• Let $\Sigma = \{ a, ., @ \}$, where $a$ represents "some letter."

• Let's make a regex for email addresses.

\[
a^+ (a^+)@a^+(a^+)\]

- cs103@cs.stanford.edu
- first.middle.last@mail.site.org
- dot.at@dot.com
For Comparison

\( a^+ (\cdot a^+) \ast \cdot a^+ (\cdot a^+) \ast \)

\begin{align*}
q_0 \quad a &\rightarrow q_1 \\
q_1 \quad \cdot &\rightarrow q_2 \\
q_2 \quad @ &\rightarrow q_8 \\
q_3 \quad a &\rightarrow q_4 \\
q_4 \quad \cdot &\rightarrow q_5 \\
q_5 \quad a &\rightarrow q_6 \\
q_6 \quad a &\rightarrow q_7 \\
q_7 \quad \cdot &\rightarrow q_8 \\
q_8 \quad \cdot &\rightarrow q_8
\end{align*}

\( \Sigma \)
Shorthand Summary

- $R^n$ is shorthand for $RR \ldots R$ ($n$ times).
  - Edge case: define $R^0 = \varepsilon$.
- $\Sigma$ is shorthand for “any character in $\Sigma$.”
- $R?$ is shorthand for $(R \cup \varepsilon)$, meaning “zero or one copies of $R$.”
- $R^+$ is shorthand for $RR^*$, meaning “one or more copies of $R$.”
Time-Out for Announcements!
Midterm Exam Logistics

• The next midterm is **Monday, February 26th** from **7:00PM - 10:00PM**. Locations are divvied up by last (family) name:
  • A-I: Go to *Cubberley Auditorium*.
  • J-Z: Go to *Cemex Auditorium*.
• The exam focuses on Lecture 06 – 13 (binary relations through induction) and PS3 – PS5. Finite automata onward is *not* tested.
  • Topics from earlier in the quarter (proofwriting, first-order logic, set theory, etc.) are also fair game, but that’s primarily because the later material builds on this earlier material.
• The exam is closed-book, closed-computer, and limited-note. You can bring a double-sided, 8.5” × 11” sheet of notes with you to the exam, decorated however you’d like.
• Students with OAE accommodations: please contact us *immediately* if you haven’t yet done so. We’ll ping you about setting up alternate exams.
Practice Midterm Exam

• We'll be holding a practice midterm exam *tonight* from 7PM - 10PM in 320-105.

• The practice midterm exam is composed of what we think is a good representative sample of older midterm questions from across the years. It’s probably the best indicator of what you should expect to see.

• Course staff will be on hand to answer your questions.

• Can't make it? We'll release the practice exam and solutions online. Set up your own practice exam time with a small group and work through it under realistic conditions!
Other Practice Materials

- We’ve posted four practice midterms to the course website, with solutions.
  - We’ll post the practice exam from this evening a little bit later, bringing the total to five.
- There’s also Extra Practice Problems 2, plus all the CS103A materials.
- Need more practice? Let us know and we’ll see what we can do!
Problem Sets

• Problem Set Five solutions are now out.
  • Please read over them – there’s a lot of good stuff in there!
  • We’ll get PS5 graded and returned as soon as we can.

• Problem Set Six is out and is due this Friday at 2:30PM.
  • *Be careful about using late days here*, since the exam is on Monday.
Back to CS103!
The Power of Regular Expressions

**Theorem:** If $R$ is a regular expression, then $\mathcal{L}(R)$ is regular.

**Proof idea:** Use induction!

- The atomic regular expressions all represent regular languages.
- The combination steps represent closure properties.
- So anything you can make from them must be regular!
Thompson’s Algorithm

• In practice, many regex matchers use an algorithm called *Thompson's algorithm* to convert regular expressions into NFAs (and, from there, to DFAs).
  • Read Sipser if you’re curious!

• **Fun fact:** the “Thompson” here is Ken Thompson, one of the co-inventors of Unix!
The Power of Regular Expressions

**Theorem:** If $L$ is a regular language, then there is a regular expression for $L$.

*This is not obvious!*

**Proof idea:** Show how to convert an arbitrary NFA into a regular expression.
Generalizing NFAs
Generalizing NFAs
Generalizing NFAs

These are all regular expressions!
Generalizing NFAs

\[ q_0 \xrightarrow{ab \cup b} q_1 \]

\[ q_2 \xrightarrow{a \ast b?a^*} q_3 \]

Start state: \( q_0 \)

States: \( q_0, q_1, q_2, q_3 \)

Transitions:
- From \( q_0 \) to \( q_1 \) on \( ab \cup b \)
- From \( q_2 \) to \( q_3 \) on \( a \ast b?a^* \)
Generalizing NFAs

Note: Actual NFAs aren’t allowed to have transitions like these. This is just a thought experiment.
Generalizing NFAs

\[ q_0 \xrightarrow{ab \cup b} q_1 \]

\[ q_2 \xrightarrow{a} q_2 \xrightarrow{ab*} q_3 \]

\[ a \quad a \quad a \quad a \quad b \quad b \quad a \quad a \quad b \quad b \quad b \]
Generalizing NFAs

\[
\begin{align*}
q_0 & \xrightarrow{ab \cup b} q_1 \\
q_2 & \xrightarrow{a} q_3 \\
q_2 & \xrightarrow{a^*b?a^*} q_3 \\
\end{align*}
\]
Generalizing NFAs

\[
\begin{array}{c}
q_0 \quad \text{start} \quad ab \cup b \quad q_1 \\
q_2 \quad a \quad a^*b?a^* \quad q_3 \\
\end{array}
\]
Generalizing NFAs

![Diagram of a non-deterministic finite automaton (NFA)]

- States: $q_0$, $q_1$, $q_2$, $q_3$
- Transitions:
  - $q_0$: $ab \cup b \rightarrow q_1$
  - $q_1$: $ab^* \rightarrow q_3$
  - $q_2$: $a \rightarrow q_1$
  - $q_2$: $a^*b?a^* \rightarrow q_3$

Input string: $aababbabbb$
Generalizing NFAs

\[
\begin{align*}
q_0 & \xrightarrow{ab \cup b} q_1 \\
& \downarrow a \\
q_2 & \xrightarrow{a^*b?a^*} q_3 \\
& \uparrow \text{start}
\end{align*}
\]

Input: a a a b a a b b b
Generalizing NFAs

Diagram:
- Start state: $q_0$
- Transitions:
  - $a$: $q_0 \rightarrow q_2$
  - $ab$: $q_0 \rightarrow q_1$
  - $ab^*$: $q_1 \rightarrow q_3$
  - $a*b?a^*$: $q_2 \rightarrow q_3$

Input sequence: $a\ a\ a\ b\ a\ a\ b\ b\ b\ b$
Generalizing NFAs

\[ q_0 \xrightarrow{ab \cup b} q_1 \]
\[ q_0 \xrightarrow{a} q_2 \]
\[ q_2 \xrightarrow{ab^*?a^*} q_3 \]

Input: \[ a \ a \ a \ a \ b \ a \ a \ b \ b \ b \]
Generalizing NFAs

Start state: $q_0$

Transitions:
- $q_0 \rightarrow a \rightarrow q_2$
- $q_0 \rightarrow ab \rightarrow q_1$
- $q_1 \rightarrow ab^* \rightarrow q_3$
- $q_2 \rightarrow a^*b?a^* \rightarrow q_3$
- $q_3 \rightarrow b^*$

Input alphabet: $a, b$
Generalizing NFAs

\[ q_0 \xrightarrow{ab \cup b} q_1 \]
\[ q_0 \xrightarrow{a} q_2 \]
\[ q_2 \xrightarrow{ab^*} q_3 \]
\[ q_2 \xrightarrow{a*b?a^*} q_3 \]

Input: a a a b a a b b b
**Key Idea 1:** Imagine that we can label transitions in an NFA with arbitrary regular expressions.
Generalizing NFAs

![Diagram showing a non-deterministic finite automaton (NFA) with states $q_0$ and $q_1$, labeled with transitions $ab \cup b$.]
Generalizing NFAs

Is there a simple regular expression for the language of this generalized NFA?
Generalizing NFAs

Is there a simple regular expression for the language of this generalized NFA?
Generalizing NFAs

\[
\begin{align*}
q_0 &\xrightarrow{a^+ (.a^+)* @ a^+ (.a^+)^+} q_1
\end{align*}
\]
Generalizing NFAs

Is there a simple regular expression for the language of this generalized NFA?
Generalizing NFAs

Is there a simple regular expression for the language of this generalized NFA?
**Key Idea 2:** If we can convert an NFA into a generalized NFA that looks like this...

...then we can easily read off a regular expression for the original NFA.
From NFAs to Regular Expressions
From NFAs to Regular Expressions

Here, $R_{11}$, $R_{12}$, $R_{21}$, and $R_{22}$ are arbitrary regular expressions.
From NFAs to Regular Expressions

Question: Can we get a clean regular expression from this NFA?
Key Idea 3: Somehow transform this NFA so that it looks like this:
The first step is going to be a bit weird...
From NFAs to Regular Expressions
From NFAs to Regular Expressions
From NFAs to Regular Expressions
From NFAs to Regular Expressions
From NFAs to Regular Expressions

Could we eliminate this state from the NFA?
From NFAs to Regular Expressions

\[
\begin{align*}
q_s & \xrightarrow{\varepsilon} q_1 \xrightarrow{R_{12}} q_2 \xrightarrow{\varepsilon} q_f \\
q_1 & \xrightarrow{R_{11}} q_s \\
q_2 & \xrightarrow{R_{21}} q_1 \\
q_f & \xrightarrow{\varepsilon} q_2 
\end{align*}
\]
From NFAs to Regular Expressions
From NFAs to Regular Expressions

Note: We’re using concatenation and Kleene closure in order to skip this state.
From NFAs to Regular Expressions
From NFAs to Regular Expressions

Start state $q_s$ to $q_1$ with $\varepsilon R_{11}$, then $R_{11}$ to $q_2$.

$q_1$ to $q_2$ with $R_{12}$.

$q_2$ to $q_f$ with $\varepsilon R_{22}$.

Expression: $\varepsilon R_{11} \ast R_{12}$.
From NFAs to Regular Expressions

\[ \varepsilon R_{11} \ast R_{12} \]
From NFAs to Regular Expressions

What regex should go on this edge?

A. $R_{12} \ R_{21}$  
B. $R_{12} \ R_{22}^* \ R_{21}$  
C. $R_{21} \ R_{12}$  
D. $R_{21} \ R_{11}^* \ R_{12}$

Answer at PollEv.com/cs103 or text CS103 to 22333 once to join, then A, B, C, or D.
From NFAs to Regular Expressions

\[ \varepsilon R_{11} \ast R_{12} \]

\[ R_{21} \ast R_{11} \ast R_{12} \]
From NFAs to Regular Expressions

\[ \varepsilon R_{11}^* R_{12} \]

\[ R_{11} \quad R_{12} \quad R_{21} \quad R_{22} \]

\[ R_{21} R_{11}^* R_{12} \]
From NFAs to Regular Expressions
From NFAs to Regular Expressions

\[
R_{11} \ast R_{12}
\]

\[
R_{21} \ast R_{11} \ast R_{12}
\]

\[
R_{22}
\]
From NFAs to Regular Expressions

\[ R_{11} \ast R_{12} \]

\[ R_{22} \cup R_{21} R_{11} \ast R_{12} \]

Note: We’re using \textit{union} to combine these transitions together.
From NFAs to Regular Expressions

\[ R_{22} \cup R_{21} \cdot R_{11}^* \cdot R_{12} \]
From NFAs to Regular Expressions

\[ R_{11} \ast R_{12} \]
From NFAs to Regular Expressions

\[ q_s \xrightarrow{R_{11} \ast R_{12}} q_2 \xrightarrow{\varepsilon} q_f \]

\[ R_{22} \cup R_{21} R_{11} \ast R_{12} \]
From NFAs to Regular Expressions
From NFAs to Regular Expressions

\[ R_{11} * R_{12} (R_{22} \cup R_{21} R_{11} * R_{12})^* \varepsilon \]
From NFAs to Regular Expressions

\[ R_{11} \ast R_{12} (R_{22} \cup R_{21} R_{11} \ast R_{12}) \ast \varepsilon \]
From NFAs to Regular Expressions

$$R_{11}^* R_{12} \ (R_{22} \cup R_{21} R_{11}^* R_{12})^* \varepsilon$$
From NFAs to Regular Expressions

\[ R_{11} \ast R_{12} (R_{22} \cup R_{21} R_{11} \ast R_{12})^* \]
From NFAs to Regular Expressions

\[ R_{11}^* R_{12} (R_{22} \cup R_{21} R_{11}^* R_{12})^* \]
From NFAs to Regular Expressions

\[
q_s \xrightarrow{R_{11}^* R_{12} (R_{22} \cup R_{21} R_{11}^* R_{12})^*} q_f
\]

\[
q_1 \xrightarrow{R_{11}} \xrightarrow{R_{12}} q_2 \xleftarrow{R_{21}} \xleftarrow{R_{22}}
\]
The Construction at a Glance

• Start with an NFA \( N \) for the language \( L \).
• Add a new start state \( q_s \) and accept state \( q_f \) to the NFA.
  • Add an \( \epsilon \)-transition from \( q_s \) to the old start state of \( N \).
  • Add \( \epsilon \)-transitions from each accepting state of \( N \) to \( q_f \), then mark them as not accepting.
• Repeatedly remove states other than \( q_s \) and \( q_f \) from the NFA by “shortcutting” them until only two states remain: \( q_s \) and \( q_f \).
• The transition from \( q_s \) to \( q_f \) is then a regular expression for the NFA.
Eliminating a State

- To eliminate a state $q$ from the automaton, do the following for each pair of states $q_0$ and $q_1$, where there's a transition from $q_0$ into $q$ and a transition from $q$ into $q_1$:
  - Let $R_{in}$ be the regex on the transition from $q_0$ to $q$.
  - Let $R_{out}$ be the regex on the transition from $q$ to $q_1$.
  - If there is a regular expression $R_{stay}$ on a transition from $q$ to itself, add a new transition from $q_0$ to $q_1$ labeled $((R_{in}) (R_{stay})^* (R_{out}))$.
  - If there isn't, add a new transition from $q_0$ to $q_1$ labeled $((R_{in}) (R_{out}))$
  - If a pair of states has multiple transitions between them labeled $R_1, R_2, \ldots, R_k$, replace them with a single transition labeled $R_1 \cup R_2 \cup \ldots \cup R_k$. 
Our Transformations

DFA → NFA → Regexp

- Direct conversion
- Subset construction
- State elimination
- Thompson's algorithm
**Theorem:** The following are all equivalent:

- \( L \) is a regular language.
- There is a DFA \( D \) such that \( \mathcal{L}(D) = L \).
- There is an NFA \( N \) such that \( \mathcal{L}(N) = L \).
- There is a regular expression \( R \) such that \( \mathcal{L}(R) = L \).
Why This Matters

- The equivalence of regular expressions and finite automata has practical relevance.
  - Tools like `grep` and `flex` that use regular expressions capture all the power available via DFAs and NFAs.
- This also is hugely theoretically significant: the regular languages can be assembled “from scratch” using a small number of operations!
Next Time

- **Applications of Regular Languages**
  - Answering “so what?”
- **Intuiting Regular Languages**
  - What makes a language regular?
- **The Myhill-Nerode Theorem**
  - The limits of regular languages.