02-0: **Alphabets & Strings**

- An **alphabet** Σ is a finite set of symbols
  - Σ_1 = $\{$a, b, . . ., z$\}$
  - Σ_2 = $\{$0, 1$\}$
- A **string** is a finite sequence of symbols from an alphabet
  - fire, truck are both strings over $\{$a, . . ., z$\}$
- length of a string is the number of symbols in the string
  - $|$fire$|$ = 4, $|$truck$|$ = 5

02-1: **Alphabets & Strings**

- The **empty string** ϵ is a string of 0 characters
  - $|\epsilon| = 0$
- $\circ$ is the **concatenation** operator
  - w_1 = fire, w_2 = truck
  - $w_1 \circ w_2$ = firetruck
  - $w_2 \circ w_1$ = truckfire
  - $w_2 \circ w_2$ = trucktruck
- Often drop the $\circ$: $w_1 w_2$ = firetruck
- For any string w, $w\epsilon = w$

02-2: **Concatenation & Reversal**

- We can concatenate a string with itself:
  - $w^1 = w$
  - $w^2 = ww$
  - $w^3 = www$
- By definition, $w^0 = \epsilon$
- Can reverse a string: w^R
  - truck^R = kcurt

02-3: **Formal Language**

- A **formal language** (or just **language**) is a set of strings
  - $L_1 =$$\{$a, aa, abba, bbba$\}$
  - $L_2 =$$\{$car, truck, goose$\}$
  - $L_3 =$$\{$1, 11, 111, 1111, 11111, . . .$\}$
- A language can be either finite or infinite

02-4: **Language Concatenation**

- We can concatenate languages as well as strings
- $L_1L_2 = \{wv : w \in L_1 \wedge v \in L_2\}$
- {a, ab}{bb, b} =

02-5: **Language Concatenation**

- We can concatenate languages as well as strings
- $L_1L_2 = \{wv : w \in L_1 \wedge v \in L_2\}$
- {a, ab}{bb, b} = {abb, ab, abbb}
- {a, ab}{a, ab} =

02-6: **Language Concatenation**

- We can concatenate languages as well as strings
- $L_1L_2 = \{wv : w \in L_1 \wedge v \in L_2\}$
- {a, ab}{bb, b} = {abb, ab, abbb}
- {a, ab}{a, ab} = {aa, aab, aba, abab}
- {a, aa}{a, aa} =

02-7: **Language Concatenation**

- We can concatenate languages as well as strings
- $L_1L_2 = \{wv : w \in L_1 \wedge v \in L_2\}$
- {a, ab}{bb, b} = {abb, ab, abbb}
- {a, ab}{a, ab} = {aa, aab, aba, abab}
- {a, aa}{a, aa} = {aa, aaa, aaaa}

What can we say about $|L_1L_2|$, if we know $|L_1| = m$ and $|L_2| = n$?

02-8: **Language Concatenation**

- We can concatenate a language with itself, just like strings
  - $L^1 = L, L^2 = LL, L^3 = LLL$, etc.
  - What should L^0 be, and why?

02-9: **Language Concatenation**

- We can concatenate a language with itself, just like strings
  - $L^1 = L, L^2 = LL, L^3 = LLL$, etc.
  - $L^0 = \{\epsilon\}$
    - {} is the empty language

- $\{\epsilon\}$ is the trivial language

- Kleene Closure (L^*)
  - $L^* = L^0 \cup L^1 \cup L^2 \cup L^3 \cup \ldots$

02-10: **Regular Expressions**

- Regular expressions are a way to describe formal languages
- Regular expressions are defined recursively
  - Base case – simple regular expressions
  - Recursive case – how to build more complex regular expressions from simple regular expressions

02-11: **Regular Expressions**

- ϵ is a regular expression, representing $\{\epsilon\}$
- $\emptyset$ is a regular expression, representing $\{\}$
- $\forall$a $\in \Sigma$, a is a regular expression representing $\{$a$\}$
- if r_1 and r_2 are regular expressions, then $(r_1 r_2)$ is a regular expression
  - $L[(r_1 r_2)] = L[r_1] \circ L[r_2]$
- if r_1 and r_2 are regular expressions, then $(r_1 + r_2)$ is a regular expression
  - $L[(r_1 + r_2)] = L[r_1] \cup L[r_2]$
- if r is regular expressions, then (r^*) is a regular expression
  - $L[(r^*)] = (L[r])^*$

02-12: **Regular Expressions**

Regular Expression Definition

Regular Expression	Language
ϵ	$L[\epsilon] = \{\epsilon\}$
$\emptyset$	$L[\emptyset] = \{\}$
$\mathtt{a} \in \Sigma$	$L[\mathtt{a}] = \{\mathtt{a}\}$
$(r_1 r_2)$	$L[r_1 r_2] = L[r_1]L[r_2]$
$(r_1 + r_2)$	$L[(r_1 + r_2)] = L[r_1] \bigcup L[r_2]$
(r^*)	$L[(r^*)] = (L[r])^*$

02-13: **Regular Expressions**

- (((a+b)(b*))a)
- ((a((a+b)*))a)
- ((a*)(b*))
- ((ab)*)

02-14: **Regular Expressions**

- (((a+b)(b*))a)

  - {aa, ba, aba, bba, abba, bbba, abbba, bbbba, . . .}
- ((a((a+b)*))a)
  - {aa, aaa, aba, aaaa, aaba, abaa, abba, . . .}
- ((a*)(b*))
  - {ϵ, a, b, aa, ab, bb, aaa, aab, abb, bbb, . . .}
- ((ab)*)
  - {ϵ, ab, abab, ababab, abababab, . . .}

02-15: **Regular Expressions**

- All those parenthesis can be confusing
  - Drop them!!
- (((ab)b)a) becomes abba
- What about a+bb*a – what's the problem?

02-16: **Regular Expressions**

- All those parenthesis can be confusing
  - Drop them!!
- (((ab)b)a) becomes abba
- What about a+bb*a – what's the problem?
  - Ambiguous!
  - a+(b(b*))a, (a+b)(b*)a, (a+(bb))*a ?

02-17: **r.e. Precedence**
From highest to Lowest:

Kleene Closure *
Concatenation
Alternation +

ab*c+e = (a(b*)c) + e

(We will still need parentheses for some regular expressions: (a+b)(a+b))

02-18: **Regular Expressions**

- Intuitive Reading of Regular Expressions
  - Concatenation == "is followed by"
  - + == "or"
  - * == "zero or more occurances"

- (a+b)(a+b)(a+b)
- (a+b)*
- aab(aa)*

02-19: **Regular Expressions**

- All strings over {a,b} that start with an a

02-20: **Regular Expressions**

- All strings over {a,b} that start with an a
    - a(a+b)*
- All strings over {a,b} that are even in length

02-21: **Regular Expressions**

- All strings over {a,b} that start with an a
    - a(a+b)*
- All strings over {a,b} that are even in length
    - ((a+b)(a+b))*
- All strings over {0,1} that have an even number of 1's.

02-22: **Regular Expressions**

- All strings over {a,b} that start with an a
    - a(a+b)*
- All strings over {a,b} that are even in length
    - ((a+b)(a+b))*
- All strings over {0,1} that have an even number of 1's.
    - 0*(10*10*)*
- All strings over a, b that start and end with the same letter

02-23: **Regular Expressions**

- All strings over {a,b} that start with an a
    - a(a+b)*
- All strings over {a,b} that are even in length
    - ((a+b)(a+b))*
- All strings over {0,1} that have an even number of 1's.
    - 0*(10*10*)*

- All strings over a, b that start and end with the same letter
  - a(a+b)*a + b(a+b)*b + a + b

02-24: **Regular Expressions**

- All strings over {0, 1} with no occurrences of 00

02-25: **Regular Expressions**

- All strings over {0, 1} with no occurrences of 00
  - 1*(011*)*(0+1*)
- All strings over {0, 1} with exactly one occurrence of 00

02-26: **Regular Expressions**

- All strings over {0, 1} with no occurrences of 00
  - 1*(011*)*(0+1*)
- All strings over {0, 1} with exactly one occurrence of 00
  - 1*(011*)*00(11*0)*1*
- All strings over {0, 1} that contain 101

02-27: **Regular Expressions**

- All strings over {0, 1} with no occurrences of 00
  - 1*(011*)*(0+1*)
- All strings over {0, 1} with exactly one occurrence of 00
  - 1*(011*)*00(11*0)*1*
- All strings over {0, 1} that contain 101
  - (0+1)*101(0+1)*
- All strings over {0, 1} that do not contain 01

02-28: **Regular Expressions**

- All strings over {0, 1} with no occurrences of 00
  - 1*(011*)*(0+1*)
- All strings over {0, 1} with exactly one occurrence of 00
  - 1*(011*)*00(11*0)*1*
- All strings over {0, 1} that contain 101
  - (0+1)*101(0+1)*
- All strings over {0, 1} that do not contain 01

  - 1*0*

02-29: **Regular Expressions**

- All strings over {/, "*", a, . . ., z } that form valid C comments
  - Use quotes to differentiate the "*" in the input from the regular expression *
  - Use [a-z] to stand for (a + b + c + d + . . . + z)

02-30: **Regular Expressions**

- All strings over {/, "*", a, . . ., z } that form valid C comments
  - Use quotes to differentiate the "*" in the input from the regular expression *
  - Use [a-z] to stand for (a + b + c + d + . . . + z)
  - /"*"([a-z]+/)* ("*"("*")*[a-z]([a-z]+/)*)* "*"("*")*/
  - This exact problem (finding a regular expression for C comments) has actually been used in an industrial context.

02-31: **Regular Languages**

- A language is **regular** if it can be described by a regular expression.
- The **Regular Languages**(L_{REG}) is the set of all languages that can be represented by a regular expression
  - Set of set of strings
- Raises the question: Are there languages that are not regular?
  - Stay tuned!