Theory of Computing

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1.1 Nondeterministic Finite Automata

1.1.1 DFA Review

- DFA's are 5-tuples with
  - δ: Q $\times$ $\Sigma \rightarrow$ Q
  - The number of transitions, δ, is $|Q||\Sigma|$
- There is no real decision-making here, an input is simply being used alongside a rule to find an output

1.1.2 NFA's

- NFAs are also a 5-tuple
- δ: Q $\times$ $\Sigma \rightarrow$ p(Q)
- $|P(Q)| = 2^{|Q|}$

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2.1 Closure Introduction

- The language recognized by a DFA, M, (L(M)) is the set of all string accepted by M
- Thus, M = (Q, Σ, δ, q_0,F)
- And Σ* is the universe of all possible inputs to M
- $\forall$ strings w $\in$ Σ*, M either accepts or rejects w
- It follows that L(M) $\subset$ Σ*
- And $\neg$ L(M) = Σ* - L(M)
- Therefore, M accepts every string in L(M) and rejects everything in $\neg$ L(M)

2.2 Closure Continued

- A set, A, is closed under a binary operation, OP, if $\forall$ x , y $\in$ A [x OP y $\in$ A]
- Ex. Natural Numbers ($\mathbb{N}$)
  1. $\mathbb{N}$ is closed under +
  2. $\mathbb{N}$ is closed under $\times$
  3. $\mathbb{N}$ is not closed under -
  4. $\mathbb{N}$ is not closed under \
- The class of all languages that are recognized by DFAs is closed under $\cup$

2.3 Closure Properties of DFAs

- Union ($\cup$)
- Intersection ($\cap$)
- Complement ($\neg$)
- Reverse

2.4 Applying Closure Properties

- If $L(M_1) \cup L(M_2)$ are DFAs, then $\exists$ DFA, M, with $L(M) = L(M_1) \cup L(M_2)$
- The purpose of a state machine is to make a yes/no decision

2.4.1 Premise:

- $M_1 = \{Q_1, \Sigma, \delta_1, q_{0_1}, F_1\}$ and $M_2 = \{Q_2, \Sigma, \delta_2, q_0, F_2\}$ are DFAs
- M_1 accepts binary strings ending in 1
- M_2 accepts binary strings of odd length
- $L(M) = L(M_1) \cup L(M_2)$
  - Accepts binary strings that either end in 1 OR have odd length (or both)
- M_1: q_1, q_2 distinguished between ending in 0 and 1
- M_2: r_1, r_2 distinguished between odd and even length
- Accordingly, M must be able to distinguish between:
  - even length ending in 1
  - even length ending in 0
  - odd length ending in 1
  - odd length ending in 0

2.4.2 Coding M

- Consider $Q = Q_1 \cdot Q_2 = \{q_1r_1, q_2r_1, q_1r_2, q_2r_2\}$
- wherein
  - q_1r_1 = even string ending in 0
  - q_1r_2 = odd string ending in 0
  - q_2r_1 = even string ending in 1
  - q_2r_2 = odd string ending in 1
- Ex. $\delta(q_1r_1, 1) = q_1r_2$
- Applying this logic to a DFA, we know that

- Q={q1r1,q1r2,q2r1,q2r2};
- S={0,1};
- d:Q *sigma $\rightarrow$ Q;
- d(q1r1,0)=q1r2;
- d(q1r1,1)=q2r2;
- d(q1r2,0)=q1r1;
- d(q1r2,1)=q2r1;
- d(q2r1,0)=q1r2;
- d(q2r1,1)=q2r2;
- d(q2r2,0)=q1r1;
- d(q2r2,1)=q2r1;
- q0=q1r1;
- F={q1r2,q2r1,q2r2};

2.4.3 Derivation

- Construct M and show that $\mathrm{L(M)} = \mathrm{L(M_1)} \cup \mathrm{L(M_2)}$.
- $\mathrm{Q} = \mathrm{Q_1} \cdot \mathrm{Q_2}$
- let $\mathrm{q_i} \in \mathrm{Q_1}$ and let $\mathrm{r_j} \in \mathrm{Q_2}$. and let $\mathrm{c} \in \Sigma$
- and $\mathrm{q_i r_j} \in \mathrm{Q}$
- thus, $\delta(\ \mathrm{q_i r_j,c}) = \delta_1(\mathrm{q_i,c})\delta_2(\mathrm{r_j,c})$
- and $\mathrm{q_0} = \mathrm{q_{01},q_{02}}$
- so that $\mathrm{F}=\{\mathrm{q_i r_j}\text{: } \mathrm{q_i} \in \mathrm{F_1} \cup \mathrm{r_j} \in \mathrm{F_2}\}$

2.4.4 Correctness

- Show that M accepts exactly the strings that are accepted by $\mathrm{M_1}$ or $\mathrm{M_2}$
- If $\mathrm{w} \in \Sigma^*$. tjem w is accepted by M and w is accepted by either $\mathrm{M_1}$ or M{2}
- To do this, we can organize Σ^* into strings of length 0, length 1, length 2...
- We solve with mathematical induction, which is how we prove recurrence relationships

2.4.5 Mathematical Induction

- Need base case and induction hypothesis
- Induction hypothesis says something is true about k, where k is the length of strings
- δ^* ($\mathrm{q_0}$,w) is the ending state of M on w where
- δ^* ($\mathrm{q_0}$,w) = $\delta^*{}_1(\mathrm{q_{01}},\mathrm{w})\delta^*{}_2(\mathrm{q_{02}},\mathrm{w})$

- Induction Hypothesis: If |w| = k, then δ*(q_0,w) $\in$ F $\iff$ δ*$_1$(q_{0_1},w) $\in$ F_1 or δ*$_2$(q_{02},w) inf F_2
- Let x $\in$ Σ.
- Then |w $\cdot$ x| = k+1
- And δ*($q_{0,wx}$) = δ*$_1$(q_{01},wx)δ*$_2$(q_{02},wx)
- If δ*$_1$(q_{01},wx) $\in$ F_1, δ*($q_{0,wx}$) $\in$ F
- Similarly, if delta*$_2$(q_{02},wx), then δ*($q_{0,wx}$) $\in$ F

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3.1 Deterministic Finite Automata

- We know that δ = Q $\times$ Σ $\rightarrow$ Q_2
- We want a function that takes a starting state and a string, then returns the state after the machine has read that string
- Let's define δ* = Q $\times$ Σ* $\rightarrow$ Q
  - δ* takes a state and a string
  - δ takes a state and a symbol
- Now, we need a recursive definition
  - Base case:
    * Let q_i $\in$ Q
    * δ*(q_i,ϵ) = q_i
  - Recursive step:
    * If q_i $\in$ Q, w $\in$ Σ*, and c $\in$ Σ
    * then δ*(q, w $\cdot$ c) = δ(δ*(q_i,w),c)

3.2 Aside: On Σ and Σ*

- Σ* is the universe of all strings over Σ
  - Σ = {0,1}
  - Σ* = {ϵ,0,1,00,01,11,10,000,...}
- We can see this recursively
  - Base step: ϵ $\in$ Σ*
  - Recursive step:
  - Let w $\in$ Σ*, let c $\in$ Σ
  - Then w $\times$ c $\in$ Σ*
- We can see this recursion graphically

w	c	w · c	step
ϵ		-	base
ϵ	1	1	recursive
1	0	10	recursive
10	1	101	recursive

3.3 Recursively Testing 101

- Solve δ*(q_1,101)
- δ(δ*(q_1,10),1)
- δ*(q_1,10)
- δ(δ*(q_1,1),0)

3.3.1 TODO Complete Recursion Sequence

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4.1 Tuples & DFAs

- Tuples are sequences which are always finite in length
- The deterministic finite automaton shown is a 5-tuple:
  1. Q: finite nonempty set of states
     - state: configuration of logic of a machine
  2. Σ (Sigma) - input alphabet
     - alphabet: a finite, nonempty set of symbols where symbols are an object of length 1
  3. δ (Delta) - transition function
  4. $Q_0 \in Q$ - starting state
  5. $F \subset Q$ - set of final states
- For this deterministic finite automaton,
  - δ: $Q \times \Sigma \to Q_2$

  Represented as a table,

Step	State	Input	Transition
1	Q_1	1	$Q_1 \to Q_2$
2	Q_2	0	$Q_2 \to Q_1$
3	Q_1	1	$Q_1 \to Q_2$
4	Q_2	1	$Q_2 \to Q_2$

4.2 Domains & Codomains

- Domain: set of all possible function inputs
- Codomain: set of all possible outputs

4.3 Strings

- In computer science, strings are character arrays
- In mathematics, strings are sequences of symbols
- Specifically a string over an alphabet, Σ, is a sequence of symbols belonging to Σ
- ϵ is the empty string
- Concatenation: If $\mathrm{w}_1, \mathrm{w}_2 \in \Sigma$, $\mathrm{w}_1 \cdot \mathrm{w}_2 = \mathrm{w}_1\mathrm{w}_2$
- If $\mathrm{c} \in \Sigma$, then $\epsilon \cdot \mathrm{c} = \mathrm{c} \cdot \epsilon = \mathrm{c}$

4.4 TODO Review Recursive Definitions

- Base step: a step that can not be broken down any further, a fact that is always true regardless of the input
- Recursive step:
- Defining the length of a string over Σ
  - Base: $|\epsilon| = 0$
  - Recursive:
    - let w be a string over Σ, and $\mathrm{c} \in \Sigma$
    - then $|\mathrm{w} \cdot \mathrm{c}| = |\mathrm{w}| + 1$
- Using this to define $|1011|$,
  1. $|1011| = |101 \cdot 1| = |101| + 1 =$
  2. $|10 \cdot 1| + 1 = |10| + 1 + 1 =$
  3. $|1 \cdot 0| + 1 + 1 = |1| + 1 + 1 + 1 =$
  4. $|\epsilon \cdot 1| + 1 + 1 + 1 =$
  5. $|\epsilon| + 1 + 1 + 1 + 1 =$
  6. $0 + 1 + 1 + 1 + 1 = 4$

4.5 Languages

- Languages over Σ - a set of finite strings over Σ
- Langauges recognized by an automaton, M, L(M) is the language accepted by M
- $\emptyset$ is the empty language
- $\epsilon \neq \emptyset$
- $\epsilon \neq \{\epsilon\}$
- ϵ is not a symbol in any alphabet

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5.1 Automaton (automata)

- Self running machine requiring a continuous power source
  - Historically used power sources include water, steam, and electricity
- Course revolves around defining the mathematics powering machines

5.2 The Mathematics of Automata

5.2.1 Mathematicians & History

- Cantor defines sets as collections of objects
- Cantor also argues that infinites can be of different magnitudes - there are infinitely more real numbers than natural numbers
- Goedel eventually derives his incompleteness theorem
  - No logical system that contains the natural numbers can prove its own soundness
  - Every sound logical system containing the natural numbers contains valid statements that cannot be proved or disproved
- In 1936, Turing proves The Halting Problem is not decidable, it is impossible
  - The Halting Problem is an algorithm that can analyze any other algorithm and determine whether or not it goes into an infinite loop
- Turing creates the turing machine as an object consisting of sets and processes wherein the object can use any finite process to complete an action.
- Turing machine sets the basis for a computer, which leads to a series of important questions:
  - What can & can't a machine do?
  - What does it mean for a problem ot be harder than another?
  - What does it mean for a machine to be more powerfule than another?

5.2.2 Sequential Logic

- Sentential Logic- based on boolean results
  - Predicated on AND, OR, NOT
  - XOR, XAND, etc. can be derived using the above

5.3 Necessary Review

- Textbook Ch. 0
- Logic Statements
- Set Theory
- Functions

5.4 Functions

- Functions - something that maps objects from one set to another
- Given f: a $\rightarrow$ b;
  - Everything in a is mapped to something in b
    - For every x, such that x is an element of a, there exists a y, such that y is an element of b
  - No one point in the domain can be mapped to two different points in the codomain
    - Logically, you can't have a function that takes in one input and returns two different outputs
    - If f maps x $\rightarrow$ y1 and $\rightarrow$ y2, y1 = y2

  -$\forall$ x $\in$ A y_1,y_2 $\in$ B [f(x)=y_1 $\wedge$ f(x)=y_2 $\rightarrow$ y_1 = y_2]

5.5 TODO Types of Functions - Definition & Logical Statement

- Injective Functions
- Surjective Functions
- Proof by Induction ($\forall$)
- Proof by Contradiction ($\neg\exists$)

5.6 Finite Automaton (Finite State Machine)

- States are logical confirgurations
- States are generally based upon input
- Purpose of a state machine is to make a yes/no decision