

Assessment 1  
Regular Languages  
and  
Logic

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# Propositional Logic

1. Model as a propositional formal the property that the initial state cannot be reached from  $c$  or  $b$

**Answer:**

$$\text{model} \rightarrow \neg((c \rightarrow a') \vee (b \rightarrow a'))$$

2. Prove the following sequent:

$$a \rightarrow b'.b \rightarrow c'.c \rightarrow b' \vdash (a \vee b) \rightarrow (b' \vee c')$$


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1.	$a \rightarrow b'.b \rightarrow c'.c \rightarrow b'$	premise
2.	$(a \rightarrow b') \wedge (b \rightarrow c') \wedge (c \rightarrow b')$	$\wedge_i$ 1
3.	$(a \rightarrow b') \wedge (c \rightarrow b') \wedge (b \rightarrow c')$	commutativity of $\wedge$ 2
4.	$(a \wedge c \rightarrow b') \wedge (b \rightarrow c')$	distributivity of $\rightarrow$ 3
5.	$a \wedge c \rightarrow b'$	$\wedge_{e1}$ 4
6.	$a \rightarrow b'$	$\wedge_{e1}$ 5
7.	$a \vee b \rightarrow b'$	$\vee_{i2}$ 6
8.	$(a \vee b) \rightarrow (b' \vee c')$	$\vee_{i2}$ 7

3. Model the property that the automate can only be in one state at a time via a definition of a propositional function

**Answer:**

$$A \oplus B \equiv (A \vee B) \wedge (\neg A \vee \neg B) \text{ [definition of the } XOR \text{ operator]}$$

$$\text{goodState}(a, b, c) \equiv (a \rightarrow b') \oplus (b \rightarrow c') \oplus (c \rightarrow b')$$

4. Negate the formula  $((a \rightarrow b') \wedge (a \wedge \neg b) \wedge (b' \wedge \neg a')) \rightarrow (b \rightarrow \neg a')$  and convert it to CNF.

- (a) Negate the formula  $\neg(((a \rightarrow b') \wedge (a \wedge \neg b) \wedge (b' \wedge \neg a')) \rightarrow (b \rightarrow \neg a'))$
- (b) Remove  $\rightarrow$  using  $A \rightarrow B \equiv \neg A \vee B$  property
  - i.  $\neg(((\neg a \vee b') \wedge (\neg a \vee \neg b) \wedge (b' \wedge \neg a')) \rightarrow (\neg b \vee \neg a'))$
  - ii.  $\neg(\neg((\neg a \vee b') \wedge (\neg a \vee \neg b) \wedge (b' \wedge \neg a')) \vee (\neg b \vee \neg a'))$
- (c) Push  $\neg$  inwards using De Morgan's Laws
  - i.  $((\neg a \vee b') \wedge (\neg a \vee \neg b) \wedge (b' \wedge \neg a')) \wedge \neg(\neg b \vee \neg a')$
  - ii.  $((\neg a \vee b') \wedge (\neg a \vee \neg b) \wedge (b' \wedge \neg a')) \wedge (b \wedge a')$
- (d) Distribute
  - i.  $b \wedge ((\neg a \vee b') \wedge (\neg a \vee \neg b) \wedge (b' \wedge \neg a')) \wedge a' \wedge ((\neg a \vee b') \wedge (\neg a \vee \neg b) \wedge (b' \wedge \neg a'))$
  - ii.  $b \wedge (\neg a \vee b') \wedge b \wedge (\neg a \vee \neg b) \wedge b \wedge (b' \wedge \neg a') \wedge a' \wedge (\neg a \vee b') \wedge a' \wedge (\neg a \vee \neg b) \wedge a' \wedge (b' \wedge \neg a')$

(e) Simplify (remove duplicate elements because  $A \wedge A \equiv A$ )

i.  $(\neg a \vee b') \wedge b \wedge (b' \wedge \neg a') \wedge (\neg a \vee \neg b) \wedge a'$

ii.  $(\neg a \vee b') \wedge b \wedge b' \wedge \neg a' \wedge (\neg a \vee \neg b) \wedge a'$

Parenthesis are dropped because:  $A \wedge B \wedge C \equiv A \wedge (B \wedge C) \equiv (A \wedge B) \wedge C$  so they all need to be *True* anyway

iii.  $\neg a' \wedge a' \wedge b \wedge b' \wedge (\neg a \vee \neg b) \wedge (\neg a \vee b')$

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**Answer:**

$$\neg a' \wedge a' \wedge b \wedge b' \wedge (\neg a \vee \neg b) \wedge (\neg a \vee b')$$

## 5. Explain the principle of unit propagation from DPLL, and use it to show that CNF formula of the previous question is unsatisfiable.

### 1. Answer:

Unit propagation refers to a technique that is used to simplify logical formulas. When we have a clause that *only* contains a single literal such as  $x$ , in all other clauses that contain  $x$ , we can replace it with *True* ie.  $\top$ .

### 2. Answer:

We can use it to show that the previous formula is unsatisfiable by demonstrating that it is a contradiction. We simplify it and continue to substitute *True* ie  $\top$  for single literal clauses.

(a)  $\neg a' \wedge a' \wedge b \wedge b' \wedge (\neg a \vee \neg b) \wedge (\neg a \vee b')$

(b)  $\neg a' \wedge a' \wedge b \wedge \top \wedge (\neg a \vee \neg b) \wedge (\neg a \vee \top)$  replace all  $b$ 's with  $\top$

(c)  $\neg a' \wedge a' \wedge \top \wedge \top \wedge (\neg a \vee \perp) \wedge (\neg a \vee \top)$  replace all  $b$ s with  $\top$

(d)  $\perp \wedge \top \wedge \top \wedge \top \wedge (\neg a \vee \perp) \wedge (\neg a \vee \top)$  replace all  $a$ 's with  $\top$

When we rearrange and simplify the formula, it becomes clear that we have  $\top \perp$ , this is a contradiction, something cannot be *True* and *False* at the same time ( $\perp \wedge \top \equiv \perp$ ).

## 6. Comment on the validity of the original formula.

**Answer:**

The formula is not satisfiable and therefore not valid as satisfiability is a prerequisite for validity. In other words, because that logical statement was a contradiction (*assumed something can be False  $\perp$  and True  $\top$  at the same time*), there was no way in which it could have been true and because of that it is not valid.

# First Order Logic

1. Write a formula in first-order logic, using the parent relation, that states that two entities  $x$  and  $y$  are siblings if they share a parent

**Answer:**

$$\forall i. \forall j. \text{siblings}(i, j) \equiv (\text{parent}(x, i) = \text{parent}(x, j))$$

2. Assuming there is an equality relation  $\equiv$  on  $P$  such that  $x \equiv y$  means  $x$  and  $y$  are the same entity, write a formula in first order logic stating that every entity has two distinct parents.

**Answer:**

$$\exists!x.P(x) \equiv \exists x(P(x) \wedge \forall y(P(y) \rightarrow y = x))$$

$$\forall i. \exists!y. \exists!x(\text{parent}(x, i) \wedge \text{parent}(y, i) \wedge \neg(x \equiv y))$$

3. Prove that the following sequent is valid:

$$\text{parent}(p, q), \forall x. \forall y(\text{parent}(x, y) \rightarrow \exists z. \text{parent}(z, x)) \vdash \exists z. \text{parent}(z, p)$$

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1.	$\text{parent}(p, q)$	premise
2.	$\forall x. \forall y(\text{parent}(x, y) \rightarrow \exists z. \text{parent}(z, x))$	premise
3.	$\text{parent}(p, q) \rightarrow \exists z. \text{parent}(z, p)$	$\forall e$ 2
4.	$\text{parent}(p, q)$	1
5.	$\exists z. \text{parent}(z, p)$	modus ponens
6.	$\exists. \text{parent}(z, p)$	conclusion

4. Interpret the following formula into simple English statement

$$\forall x. \exists y. \text{parent}(y, x) \rightarrow \forall a. \exists b. \text{parent}(a, b)$$

**Answer:**

If all children have a parent, then all parents have a child.

5. The sequent below is not valid. Show this by proving a counter-example: a concrete definition of the universe  $P$  (a set) and the relation parent. Explain why this is a counterexample.

$$\vdash \forall x. \exists y. \text{parent}(y, x) \rightarrow \forall a. \exists b. \text{parent}(a, b)$$

**Answer:**

If this is not valid then:  $\forall x. \exists y. \text{parent}(y, x) \wedge \neg(\forall a. \exists b. \text{parent}(a, b))$ , because the only way implication can be wrong is if we are concluding *False* from *True* ie  $\neg(A \rightarrow B) \equiv A \wedge \neg B$ . So I need to prove this is true by defining the Universe  $P$  (a set):

$$P = \{ x \mid \exists y. \text{parent}(y, x) \}$$

and the case that contradicts it:

$$\exists a. \exists b. \neg \text{parent}(a, b)$$

The reason this would be a counterexample is that it shows that there is an object for which the predicate *parent* does not hold, which contradicts this logical statement which is universally quantified ie. makes a claim about all objects.

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<sup>1</sup>There exists exactly one, see <https://math.stackexchange.com/questions/228285/how-can-i-get-the-negation-of-exists-unique-existential-quantification>

**6. What is the smallest possible counterexample universe  $P$  and relation parent. Explain your reasoning.**

**Answer:**

The smallest possible counterexample universe (a set) would consist of the minimum number of elements for which the predicate does not hold (here this is two). Normally one counterexample is sufficient to contradict any statement that is universally quantified. In other words  $\exists(A).\neg P(A)$  contradicts  $\forall A.P(A)$ , but because this predicate is a statement about two objects  $A$  and  $B$  we do need both to show a single case where  $P$  does not hold.

**7. Prove that the following sequent is valid.**

$$\forall x.\forall y.parent(x, y) \rightarrow \neg(x \equiv y) \vdash \neg\exists x.parent(x, x)$$


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|----|---|--|
| 1. | $\forall x.\forall y.parent(x, y) \rightarrow \neg(x \equiv y)$ | premise  |
| 2. | $parent(x_0, y_0) \rightarrow \neg(x_0 \equiv y_0)$             | $\forall_e$ 1                                    |
| 3. | $\neg parent(x_0, y_0) \vee \neg(x_0 \equiv y_0)$               | because $P \rightarrow Q \equiv \neg P \vee Q$ 2 |
| 4. | $\neg(parent(x_0, y_0) \wedge (x_0 \equiv y_0))$                | De Morgan's Law 3                                |
| 5. | $\neg parent(x_0, x_0)$   | $\wedge_e$ 4                                     |
| 6. | $\neg\exists x_0.parent(x_0, x_0)$                              | $\exists_i$ 5                                    |
| 7. | $\neg\exists x.parent(x, x)$                                    | conclusion                                       |

# Regular Languages and Finite Automata

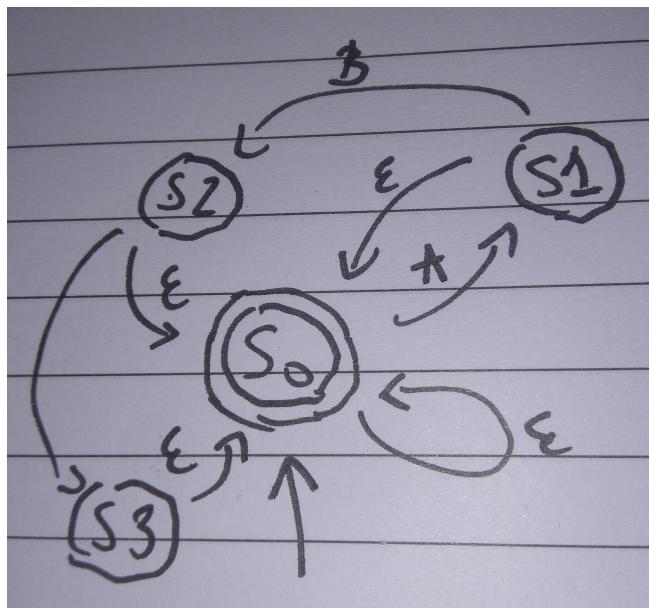
1. For the regular expression  $(A|AB|ABB)^*$  do the following steps (and justify them):

a) Translate it into an NFA

Answer:

- we need to allow an infinite loop because of \* (but also allow not to loop at all and end straight away because  $A^*$  is  $A\{0, \infty\}$ )
- we need to be able to go around that loop by having either  $\epsilon$  or  $A$  or  $AB$  or  $ABB$  as input strings.
- we need to be able to exit after any of these or loop again.

Therefore it makes sense to have a loop around the initial state which would also become the final state with  $\epsilon$  inputs leading to the final state.



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Input alphabet  $\Sigma = \{\epsilon, A, AB, ABB\}$

Initial state  $s_0$

Set of states  $S = \{s_0, S1, S2, S3\}$

Set of final states  $F = \{s_0\}$

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b) Remove (semantic preserving) the  $\epsilon$  transitions

Answer:

- The outcome of this operation *will still* be an NFA
- I will have to compute the  $\epsilon$  closure of the states ie for every state.
- I need to find the set of states reachable from that state by using  $\epsilon$  transitions (which will always include going to that state itself)

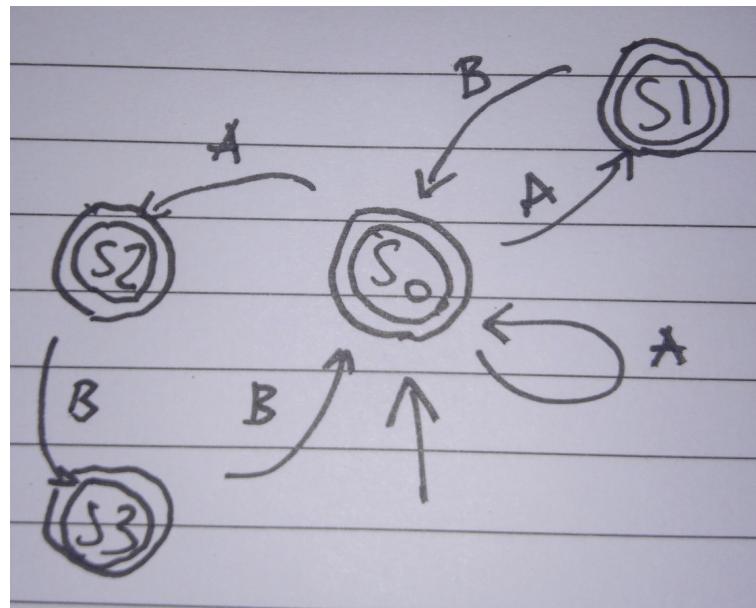
### Epsilon clojres

$s_0 \{s_0\}$

$S1 \{s_0, S1\}$

$S2 \{s_0, S2\}$

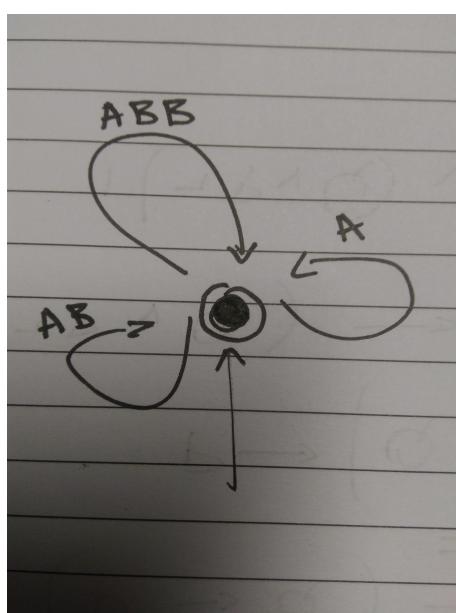
$S3 \{s_0, S3\}$



### c) Create the corresponding DFA

**Answer:**

- I need to remove any ambiguity about what state to go
- from any state  $S_n$  there needs to be at most one  $k$  transition to  $S_{n+1}$  (the next state)



**2. Consider the following language:** A word is in the language if and only if it contains an even number of *A*s an odd number of *B*s and precisely one *C*.

**Answer:**

This is not possible because Finite Automata *cannot store any states* – they don't have memory and cannot keep track of how many *A*s and *B*s have been encountered. Their only memory they have is the state they are in.

Even though many modern regular expression engines will allow counted repetitions eg  $A\{n, m\}$  ie *A* occurring  $n$  to  $m$  times, these are extensions to the traditional idea of finite automata and are not part of FSM themselves.

Having an odd or even number of *A*s would be even more difficult and perhaps impossible even using perl-style regular expressions.

Generally speaking FSM lack the expressiveness to solve this problem and context free grammars need to be used in such cases.

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## References

- [https://en.wikipedia.org/wiki/Conjunctive\\_normal\\_form](https://en.wikipedia.org/wiki/Conjunctive_normal_form)
- [https://en.wikipedia.org/wiki/De\\_Morgan%27s\\_laws](https://en.wikipedia.org/wiki/De_Morgan%27s_laws)
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