Regular expressions and Kleene's theorem

Informatics 2A: Lecture 5

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1. Closure properties of regular languages
   - ϵ-NFAs
   - Closure under concatenation
   - Closure under Kleene star
2. Regular expressions
   - From regular expressions to regular languages
3. Kleene's theorem and Kleene algebra
   - Kleene algebra
   - From DFAs to regular expressions
   - Appendix: from NFAs to regular expressions

Clicker meta-question 1

What would you consider to be the optimal number of clicker questions per lecture? (Not counting meta-questions like this one.)

A: 0

B: 1–2

C: 3–4

D: ≥ 5

Clicker meta-question 2

How challenging would you like clicker questions to be?

A: Mainly simple questions to check basic understanding

B: Mainly challenging questions

C: A mixture of simple and challenging questions

D: Whatever seems most appropriate for the material

Closure properties of regular languages

- We've seen that if both L_1 and L_2 are regular languages, so is $L_1 \cup L_2$.
- We sometimes express this by saying that regular languages are closed under the 'union' operation. ('Closed' used here in the sense of 'self-contained'.)
- We will show that regular languages are closed under other operations too: Concatenation: $L_1.L_2$ and Kleene star: L^* For these, we'll need to work with a minor variation on NFAs.
- All this will lead us to another way of defining regular languages: via regular expressions.

Concatenation and Kleene star

- Concatenation: write $L_1.L_2$ for the language

$$\{xy \mid x \in L_1, y \in L_2\}$$

E.g. if $L_1 = \{aaa\}$ and $L_2 = \{b, c\}$ then $L_1.L_2$ is the language $\{aaab,\ aaac\}$.

- Kleene star: let L^* denote the language

$$\{\epsilon\} \cup L \cup L.L \cup L.L.L \cup \ldots$$

E.g. if $L_3 = \{aaa, b\}$ then L_3^* contains strings like *aaaaaa*, *bbbbb*, *baaaaaabbaaa*, etc.
More precisely, L_3^* contains all strings over $\{a, b\}$ in which the letter a always appears in sequences of length some multiple of 3

Clicker question

Consider the language over the alphabet $\{a, b, c\}$

$$L = \{x \mid x \text{ starts with } a \text{ and ends with } c\}$$

Which of the following strings is *not* valid for the language $L.L$?

A: *abcabc*

B: *acacac*

C: *abcbcac*

D: *abcbacbc*

Clicker question

Consider the (same) language over the alphabet $\{a, b, c\}$

$$L = \{x \mid x \text{ starts with } a \text{ and ends with } c\}$$

Which of the following strings is *not* valid for the language L^* ?

A: ϵ

B: $acaca$

C: $abcbc$

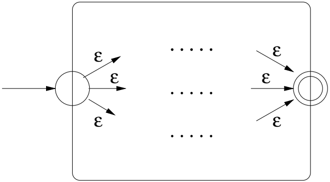
D: $acacacacac$

NFAs with ϵ-transitions

We can vary the definition of NFA by also allowing transitions labelled with the special symbol ϵ (*not* a symbol in Σ).

The automaton may (but doesn't have to) perform an ϵ-transition at any time, without reading an input symbol.

This is quite convenient: for instance, we can turn any NFA into an ϵ-NFA with just one start state and one accepting state:



(Add ϵ-transitions from new start state to each state in S, and from each state in F to new accepting state.)

Equivalence to ordinary NFAs

Allowing ϵ-transitions is just a convenience: it doesn't fundamentally change the power of NFAs.

If $N = (Q, \Delta, S, F)$ is an ϵ-NFA, we can convert N to an ordinary NFA with the same associated language, by simply 'expanding' Δ and S to allow for silent ϵ-transitions.

Formally, the ϵ-closure of a transition relation $\Delta \subseteq Q \times (\Sigma \cup \{\epsilon\}) \times Q$ is the smallest relation $\overline{\Delta}$ that contains Δ and satisfies:

- if $(q, u, q') \in \overline{\Delta}$ and $(q', \epsilon, q'') \in \Delta$ then $(q, u, q'') \in \overline{\Delta}$;
- if $(q, \epsilon, q') \in \Delta$ and $(q', u, q'') \in \overline{\Delta}$ then $(q, u, q'') \in \overline{\Delta}$.

Likewise, the ϵ-closure of S under Δ is the smallest set of states $\overline{S}_\Delta$ that contains S and satisfies:

- if $q \in \overline{S}_\Delta$ and $(q, \epsilon, q') \in \Delta$ then $q' \in \overline{S}_\Delta$.

We can then replace the ϵ-NFA (Q, Δ, S, F) with the ordinary NFA

$$(Q,\ \overline{\Delta} \cap (Q \times \Sigma \times Q),\ \overline{S}_\Delta,\ F)$$

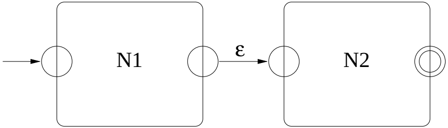
Concatenation of regular languages

We can use ϵ-NFAs to show that regular languages are closed under the concatenation operation:

$$L_1.L_2 \;=\; \{xy \mid x \in L_1, y \in L_2\}$$

If L_1, L_2 are any regular languages, choose ϵ-NFAs N_1, N_2 that define them. As noted earlier, we can pick N_1 and N_2 to have just one start state and one accepting state.

Now hook up N_1 and N_2 like this:



Clearly, this NFA corresponds to the language $L_1.L_2$.

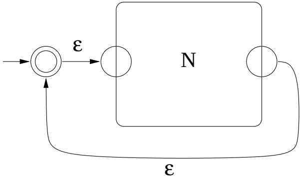
To ponder: do we need the ϵ-transition in the middle?

Kleene star

Similarly, we can now show that regular languages are closed under the Kleene star operation:

$$L^* \;=\; \{\epsilon\} \cup L \cup L.L \cup L.L.L \cup \ldots$$

For suppose L is represented by an ϵ-NFA N with one start state and one accepting state. Consider the following ϵ-NFA:



Clearly, this ϵ-NFA corresponds to the language L^*.

Regular expressions

We've been looking at ways of specifying regular languages via machines (often given by diagrams). But it's also useful to have more textual ways of defining languages.

A regular expression is a written mathematical expression that defines a language over a given alphabet Σ.

- The basic regular expressions are

$$\emptyset \qquad\qquad \epsilon \qquad\qquad a \quad (\text{for } a \in \Sigma)$$

- From these, more complicated regular expressions can be built up by (repeatedly) applying the binary operations $+, .$ and the unary operation *. Example: $(a.b + \epsilon)^* + a$

We allow brackets to indicate priority. In the absence of brackets, * binds more tightly than ., which itself binds more tightly than $+$.

$$\text{So} \quad a + b.a^* \quad \text{means} \quad a + (b.(a^*))$$

Also the dot is often omitted: ab means $a.b$

How do regular expressions define languages?

A regular expression is itself just a written expression (actually in some context-free 'meta-language'). However, every regular expression α over Σ can be seen as defining an actual language $\mathcal{L}(\alpha) \subseteq \Sigma^*$ in the following way:

- $\mathcal{L}(\boldsymbol{\emptyset}) = \emptyset, \quad \mathcal{L}(\boldsymbol{\epsilon}) = \{\epsilon\}, \quad \mathcal{L}(a) = \{a\}$.
- $\mathcal{L}(\alpha + \beta) = \mathcal{L}(\alpha) \cup \mathcal{L}(\beta)$
- $\mathcal{L}(\alpha.\beta) = \mathcal{L}(\alpha) \,.\, \mathcal{L}(\beta)$
- $\mathcal{L}(\alpha^*) = \mathcal{L}(\alpha)^*$

Example: $a + ba^*$ defines the language $\{a, b, ba, baa, baaa, \ldots\}$.

The languages defined by $\boldsymbol{\emptyset}, \boldsymbol{\epsilon}, a$ are obviously regular.

What's more, we've seen that regular languages are closed under union, concatenation and Kleene star.

This means every regular expression defines a regular language. (Proof by induction on the size of the regular expression.)

Clicker question

Consider again the language

$$\{x \in \{0,1\}^* \mid x \text{ contains an even number of 0's}\}$$

Which of the following regular expressions is *not* a possible definition of this language?

A: $(1^*01^*01^*)^*$

B: $(1^*01^*0)^*1^*$

C: $1^*(01^*0)^*1^*$

D: $(1+01^*0)^*$

Kleene's theorem

We've seen that every regular expression defines a regular language.

The main goal of today's lecture is to show the converse, that every regular language can be defined by a regular expression. For this purpose, we introduce Kleene algebra: the algebra of regular expressions.

The equivalence between regular languages and expressions is: Kleene's theorem

> *DFAs and regular expressions give rise to exactly the same class of languages (the regular languages).*

As we've already seen, NFAs (with or without ϵ-transitions) also give rise to this class of languages.

So the evidence is mounting that the class of regular languages is mathematically a very 'natural' class to consider.

Kleene algebra

Regular expressions give a textual way of specifying regular languages. This is useful e.g. for communicating regular languages to a computer.

Another benefit: regular expressions can be manipulated using algebraic laws (Kleene algebra). For example:

$$\begin{array}{rcl@{\qquad}rcl}
\alpha+(\beta+\gamma) & \equiv & (\alpha+\beta)+\gamma & \alpha+\beta & \equiv & \beta+\alpha \\
\alpha+\emptyset & \equiv & \alpha & \alpha+\alpha & \equiv & \alpha \\
\alpha(\beta\gamma) & \equiv & (\alpha\beta)\gamma & \epsilon\alpha & \equiv & \alpha\epsilon \ \equiv \ \alpha \\
\alpha(\beta+\gamma) & \equiv & \alpha\beta+\alpha\gamma & (\alpha+\beta)\gamma & \equiv & \alpha\gamma+\beta\gamma \\
\emptyset\alpha & \equiv & \alpha\emptyset \ \equiv \ \emptyset & \epsilon+\alpha\alpha^* & \equiv & \epsilon+\alpha^*\alpha\equiv\alpha^*
\end{array}$$

Often these can be used to simplify regular expressions down to more pleasant ones.

Other reasoning principles

Let's write $\alpha \leq \beta$ to mean $\mathcal{L}(\alpha) \subseteq \mathcal{L}(\beta)$ (or equivalently $\alpha + \beta \equiv \beta$). Then

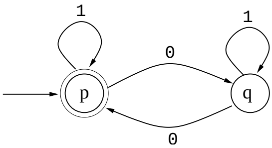
$$\begin{aligned} \alpha\gamma + \beta \leq \gamma \quad &\Rightarrow \quad \alpha^*\beta \leq \gamma \\ \beta + \gamma\alpha \leq \gamma \quad &\Rightarrow \quad \beta\alpha^* \leq \gamma \end{aligned}$$

Arden's rule: Given an equation of the form $X = \alpha X + \beta$, its smallest solution is $X = \alpha^*\beta$.

What's more, if $\epsilon \notin \mathcal{L}(\alpha)$, this is the *only* solution.

Intriguing fact: The rules on this slide and the last form a complete set of reasoning principles, in the sense that if $\mathcal{L}(\alpha) = \mathcal{L}(\beta)$, then '$\alpha \equiv \beta$' is provable using these rules. (Beyond scope of Inf2A.)

DFAs to regular expressions



For each state a, let X_a stand for the set of strings that take us from a to an accepting state. Then we can write some equations:

$$\begin{aligned} X_p &= 1.X_p + 0.X_q + \epsilon \\ X_q &= 1.X_q + 0.X_p \end{aligned}$$

Solve by eliminating one variable at a time:

$$\begin{aligned} && X_q &= 1^*0.X_p \quad \text{by Arden's rule} \\ \text{So} && X_p &= 1.X_p + 01^*0X_p + \epsilon \\ && &= (1+01^*0)X_p + \epsilon \\ \text{So} && X_p &= (1+01^*0)^* \quad \text{by Arden's rule} \end{aligned}$$

General (non-examinable) proof of Kleene's theorem: From NFAs to regular expressions

Given an NFA $N = (Q, \Delta, S, F)$ (without ϵ-transitions), we'll show how to define a regular expression defining the same language as N.

In fact, to build this up, we'll construct a three-dimensional array of regular expressions α_{uv}^X: one for every $u \in Q, v \in Q, X \subseteq Q$.

Informally, α_{uv}^X will define the set of *strings that get us from* u *to* v *allowing only intermediate states in* X.

We shall build suitable regular expressions $\alpha_{u,v}^X$ by working our way from smaller to larger sets X.

At the end of the day, the language defined by N will be given by the sum $(+)$ of the languages α_{sf}^Q for all states $s \in S$ and $f \in F$.

Construction of α_{uv}^{X}

Here's how the regular expressions α_{uv}^{X} are built up.

- If $X = \emptyset$, let $a_1, \ldots, a_k$ be all the symbols a such that $(u, a, v) \in \Delta$. Two subcases:
  - If $u \neq v$, take $\alpha_{uv}^{\emptyset} \;=\; a_1 + \cdots + a_k$
  - If $u = v$, take $\alpha_{uv}^{\emptyset} \;=\; (a_1 + \cdots + a_k) + \epsilon$

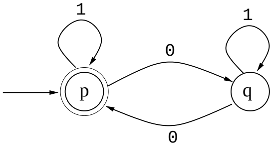
  Convention: if $k = 0$, take '$a_1 + \ldots + a_k$' to mean $\emptyset$.
- If $X \neq \emptyset$, choose any $q \in X$, let $Y = X - \{q\}$, and define

$$\alpha_{uv}^{X} \;=\; \alpha_{uv}^{Y} + \alpha_{uq}^{Y}(\alpha_{qq}^{Y})^{*}\alpha_{qv}^{Y}$$

Applying these rules repeatedly gives us $\alpha_{u,v}^{X}$ for every u, v, X.

NFAs to regular expressions: tiny example

Let's revisit our old friend:



Here p is the only start state and the only accepting state.
By the rules on the previous slide:

$$\alpha_{p,p}^{\{p,q\}} = \alpha_{p,p}^{\{p\}} + \alpha_{p,q}^{\{p\}}(\alpha_{q,q}^{\{p\}})^*\alpha_{q,p}^{\{p\}}$$

Now by inspection (or by the rules again), we have

$$\begin{array}{lcl lcl} \alpha_{p,p}^{\{p\}} & = & 1^* & \alpha_{p,q}^{\{p\}} & = & 1^*0 \\ \alpha_{q,q}^{\{p\}} & = & 1+01^*0 & \alpha_{q,p}^{\{p\}} & = & 01^* \end{array}$$

So the required regular expression is

$$1^* \; + \; 1^*0(1+01^*0)^*01^* \qquad \text{(A bit messy!)}$$

Reading

Relevant reading:

- Regular expressions: Kozen chapters 7,8; J & M chapter 2.1. (Both texts actually discuss more general 'patterns' — see next lecture.)
- From regular expressions to NFAs: Kozen chapter 8; J & M chapter 2.3.
- Kleene algebra: Kozen chapter 9, 10.
- From NFAs to regular expressions: Kozen chapter 9.

Next time: Some applications of all this theory.

- Pattern matching
- Lexical analysis