

The Pumping Lemma: limitations of regular languages

Informatics 2A: Lecture 8

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Recap of Lecture 7

- **Lexical classes** in programming languages may typically be specified via regular languages.
- The **lexing algorithm** runs a parallel NFA in order to find the next **lexeme** using the **principle of longest match**.
- Regular language theory can also be used in **verifying** subtle properties of large finite-state systems (e.g. those arising from interactions of several simpler systems).

Non-regular languages

We've hinted before that not all languages are regular. E.g.

- Java (or any other general-purpose programming language).
- The language $\{a^n b^n \mid n \geq 0\}$.
- The language of all *well-matched* sequences of brackets $(,)$.
N.B. A sequence x is well-matched if it contains the same number of opening brackets '(' and closing brackets ')', and no initial subsequence y of x contains more ')'s than '('s.

But **how do we know** these languages aren't regular?

Can we come up with a **general technique** for proving the non-regularity of languages?

The basic intuition: DFAs can't count!

Consider $L = \{a^n b^n \mid n \geq 0\}$. Just suppose, hypothetically, there were some DFA M with $\mathcal{L}(M) = L$.

Suppose furthermore that M had just processed a^n , and some continuation b^m was to follow.

Intuition: M would need to have *counted* the number of a 's, in order to know how many b 's to require.

More precisely, let q_n denote the state of M after processing a^n . Then for any $m \neq n$, the states q_m, q_n must be different, since b^m takes us to an accepting state from q_m , but not from q_n .

In other words, M would need **infinitely many states**, one for each natural number. Contradiction!

Exercises

Which of the following languages are regular?

- 1 Strings with an odd number of a 's and an even number of b 's.
- 2 Strings containing strictly more a 's than b 's.
- 3 Strings such that $(\text{no. of } a\text{'s}) \times (\text{no. of } b\text{'s}) \equiv 6 \pmod{24}$.
- 4 Strings over $\{0, \dots, 9\}$ representing integers divisible by 43.

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Answer: 1 is regular (see similar example in Lecture 4).

2 isn't regular: intuitively, we'd need to keep track of difference between no. of a 's and no. of b 's, which could be any integer.

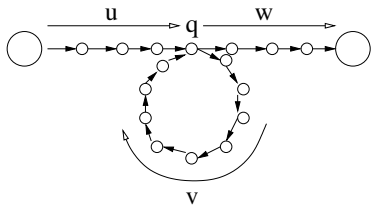
3 is regular: we only need to keep track of no. of a 's mod 24 and no. of b 's mod 24, which we can do with $24 \times 24 = 576$ states.

4 is regular: we can keep track of the number read so far mod 43.

On reading a new digit d , we go from state i to state $(10i + d) \pmod{43}$.

Loops in DFAs

Let M be a DFA with k states. Suppose, starting from some state of M , we process a string y of length $|y| \geq k$. We then pass through a sequence of $|y| + 1$ states. So there must be some state q that's visited *at least twice*:



(Note that u and w might be ϵ , but v definitely isn't.)

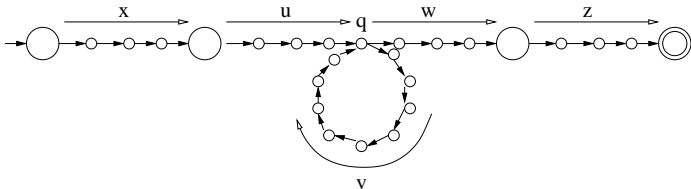
So any string y with $|y| \geq k$ can be decomposed as uvw , where

- u is the prefix of y that leads to the first visit of q
- v takes us once round the loop from q to q ,
- w is whatever is left of y after uv .

A general consequence

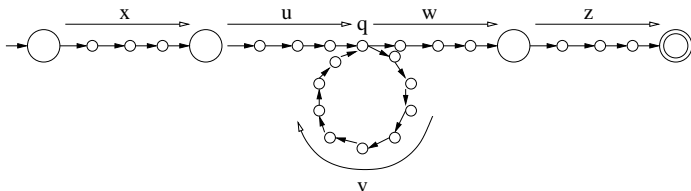
If L is *any* regular language, we can pick *some* DFA M for L , and it will have some number of states — say k .

Suppose we run M on a string $xyz \in L$, where $|y| \geq k$. There must be at least one state q visited twice in the course of processing y :



(There may be other 'revisited states' not indicated here.)

The idea of 'pumping'



So y can be decomposed as uvw , where

- xu takes M from the initial state to q ,
- $v \neq \epsilon$ takes M once round the loop from q to q ,
- wz takes M from q to an accepting state.

But now M will be oblivious to whether, or how many times, we go round the v -loop!

So we can 'pump in' as many copies of the substring v as we like, knowing that we'll still end in an accepting state.

The pumping lemma: official form

The pumping lemma basically summarizes what we've just said.

Pumping Lemma. Suppose L is a regular language. Then L has the following property.

(P) There exists $k \geq 0$ such that, for all strings x, y, z with $xyz \in L$ and $|y| \geq k$, there exist strings u, v, w such that $y = uvw$, $v \neq \epsilon$, and for every $i \geq 0$ we have $xuv^i wz \in L$.

The pumping lemma: contrapositive form

Since we want to use the pumping lemma to show a language *isn't* regular, we usually apply it in the following equivalent but back-to-front form.

Suppose L is a language for which the following property holds:

($\neg P$) For all $k \geq 0$, there exist strings x, y, z with $xyz \in L$ and $|y| \geq k$ such that, for every decomposition of y as $y = uvw$ where $v \neq \epsilon$, there is some $i \geq 0$ for which $xuv^i wz \notin L$.

Then L is not a regular language.

N.B. The pumping lemma can only be used to show a language *isn't* regular. Showing L satisfies (P) doesn't prove L is regular!

To show that a language *is* regular, give some DFA or NFA or regular expression that defines it.

The pumping lemma: a user's guide

So to show some language L is not regular, it's enough to show that L satisfies $(\neg P)$.

Note that $(\neg P)$ is quite a complex statement:

$$\forall k \dots \exists x, y, z \dots \forall u, v, w \dots \exists i \dots$$

Helpful intuition: Values for the variables quantified by \forall are chosen by an imaginary 'opponent' who is claiming that P is true. Values for the variables quantified by \exists are chosen by you.

We'll look at a simple example first, then offer some advice on the general pattern of argument.

Example 1

Consider $L = \{a^n b^n \mid n \geq 0\}$.

We show that L satisfies $(\neg P)$.

Suppose we're given $k \geq 0$. (Opponent chooses the value of k .
Our argument has to work for *all* k .)

Consider the strings $x = \epsilon$, $y = a^k$, $z = b^k$. Note that $xyz \in L$ and $|y| \geq k$ as required. (We make a cunning choice of x, y, z .)

Suppose now we're given a decomposition of y as uvw with $v \neq \epsilon$. (Opponent chooses this decomposition. Our argument has to work for all such u, v, w .)

Let $i = 0$. (We make a cunning choice of i .)

Then $uv^i w = uw = a^l$ for some $l < k$. So $xuv^i wz = a^l b^k \notin L$.
(We win!)

Thus L satisfies $(\neg P)$, so L isn't regular.

Use of pumping lemma: general pattern

On the previous slide, the full argument is in black, whereas the **parenthetical comments in blue** are for pedagogical purposes only.

The comments emphasise the care that is needed in dealing with the quantifiers in the property ($\neg P$). In general:

- **You are not allowed to choose** the number $k \geq 0$. Your argument has to work for every possible value of k .
- **You have to choose** the strings x, y, z , which might depend on k . You must choose these to satisfy $xyz \in L$ and $|y| \geq k$. Also, y should be chosen cunningly to **'disallow pumping'** ...
- **You are not allowed to choose** the strings u, v, w . Your argument has to work for every possible decomposition of y as uvw with $v \neq \epsilon$.
- **You have to choose** the number $i (\neq 1)$ such that $xuv^i wz \notin L$. Here i might depend on all the previous data.

Example 2

Consider $L = \{a^{n^2} \mid n \geq 0\}$.

We show that L satisfies $(\neg P)$:

Suppose $k \geq 0$.

Let $x = a^{k^2-k}$, $y = a^k$, $z = \epsilon$, so $xyz = a^{k^2} \in L$.

Given any splitting of y as uvw with $v \neq \epsilon$, we have $1 \leq |v| \leq k$.

Take $i = 2$. Since $xuvwz = a^{k^2}$, we have that $xuv^2wz = a^{k^2+|v|}$.

And $1 \leq |v| \leq k$ means that $k^2 + 1 \leq k^2 + |v| \leq k^2 + k$.

However, there are no perfect squares between k^2 and $k^2 + 2k + 1$.

So the length of xuv^2wz isn't a perfect square. Thus $xuv^2wz \notin L$.

Thus L satisfies $(\neg P)$, so L isn't regular.

Subtle point: what are the x and z for?

All the action seems to happen within $y = uvw$. Do we really need x and z ?

Often, we can get away with taking $x = z = \epsilon$. But other choices may of x, z may give us more control over where the 'loop' occurs.

Example: L is the set of strings containing more a 's than b 's.

- **First approach:** Given k , take $x = \epsilon$, $y = a^{k+1}b^k$, $z = \epsilon$. If $y = uvw$, we have three cases to consider, according to where v begins and ends.
- **Second approach:** Given k , take $x = a^{k+1}$, $y = b^k$, $z = \epsilon$. Only one case to consider. Taking $i = 2$ always works.

Reading and prospectus

Relevant reading: Kozen chapters 11, 12.

That concludes the course material on (formal) regular languages.

Next time, we start on the next level up in the Chomsky hierarchy:
context-free languages.