

# Theory of Computer Science

## B6. Regular Languages: Pumping Lemma

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### Pumping Lemma: Motivation



You can show that a language is regular by specifying an appropriate grammar, finite automaton, or regular expression. How can you show that a language is **not** regular?

- ▶ Direct proof that no regular grammar exists that generates the language  
     $\rightsquigarrow$  difficult in general
- ▶ **Pumping lemma**: use a necessary property that holds for all regular languages.

## Pumping Lemma

### Theorem (Pumping Lemma)

If  $L$  is a regular language then there is a number  $p \in \mathbb{N}$  (a *pumping number* for  $L$ ) such that all words  $x \in L$  with  $|x| \geq p$  can be split into  $x = uvw$  with the following properties:

- 1  $|v| \geq 1$ ,
- 2  $|uv| \leq p$ , and
- 3  $uv^i w \in L$  for all  $i = 0, 1, 2, \dots$

**Question:** what if  $L$  is finite?

## Pumping Lemma: Proof

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### Proof.

For regular  $L$  there exists a DFA  $M = \langle Q, \Sigma, \delta, q_0, E \rangle$  with  $\mathcal{L}(M) = L$ . We show that  $p = |Q|$  has the desired properties.

Consider an arbitrary  $x \in \mathcal{L}(M)$  with length  $|x| \geq |Q|$ . Including the start state,  $M$  visits  $|x| + 1$  states while reading  $x$ . Because of  $|x| \geq |Q|$  at least one state has to be visited twice. ...

## Pumping Lemma: Proof

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### Proof (continued).

Choose a split  $x = uvw$  so  $M$  is in the same state after reading  $u$  and after reading  $uv$ . Obviously, we can choose the split in a way that  $|v| \geq 1$  and  $|uv| \leq |Q|$  are satisfied. ...

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- 1  $|v| \geq 1$ ,
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- 3  $uv^i w \in L$  for all  $i = 0, 1, 2, \dots$

### Proof (continued).

The word  $v$  corresponds to a loop in the DFA after reading  $u$  and can thus be repeated arbitrarily often. Every subsequent continuation with  $w$  ends in the same end state as reading  $x$ . Therefore  $uv^i w \in \mathcal{L}(M) = L$  is satisfied for all  $i = 0, 1, 2, \dots$   $\square$

## Pumping Lemma: Application

Using the pumping lemma (PL):

### Proof of Nonregularity

- ▶ If  $L$  is regular, then the pumping lemma holds for  $L$ .
- ▶ By contraposition: if the PL does not hold for  $L$ , then  $L$  cannot be regular.
- ▶ That is: if there is no  $p \in \mathbb{N}$  with the properties of the PL, then  $L$  cannot be regular.

## Pumping Lemma: Caveat

### Caveat:

The pumping lemma is a **necessary condition** for a language to be regular, but not a **sufficient one**.

- ↪ there are languages that satisfy the pumping lemma conditions but are not regular
- ↪ for such languages, other methods are needed to show that they are not regular (e.g., the [Myhill-Nerode theorem](#))

## Pumping Lemma: Example

### Example

The language  $L = \{a^n b^n \mid n \in \mathbb{N}\}$  is not regular.

### Proof.

Assume  $L$  is regular. Then let  $p$  be a pumping number for  $L$ .

The word  $x = a^p b^p$  is in  $L$  and has length  $\geq p$ .

Let  $x = uvw$  be a split with the properties of the PL.

Then the word  $x' = uv^2w$  is also in  $L$ . Since  $|uv| \leq p$ ,  $uv$  consists only of symbols  $a$  and  $x' = a^{|u|} a^{2|v|} a^{p-|uv|} b^p = a^{p+|v|} b^p$ .

Since  $|v| \geq 1$  it follows that  $p + |v| \neq p$  and thus  $x' \notin L$ .

This is a contradiction to the PL.  $\rightsquigarrow L$  is not regular. □

## Pumping Lemma: Another Example I

### Example

The language  $L = \{ab^n ac^{n+2} \mid n \in \mathbb{N}\}$  is not regular.

### Proof.

Assume  $L$  is regular. Then let  $p$  be a pumping number for  $L$ .

The word  $x = ab^p ac^{p+2}$  is in  $L$  and has length  $\geq p$ .

Let  $x = uvw$  be a split with the properties of the PL.

From  $|uv| \leq p$  and  $|v| \geq 1$  we know that  $uv$  consists of one  $a$  followed by at most  $p - 1$   $b$ s.

We distinguish two cases,  $|u| = 0$  and  $|u| > 0$ . ...

## Pumping Lemma: Another Example II

### Example

The language  $L = \{ab^nac^{n+2} \mid n \in \mathbb{N}\}$  is not regular.

### Proof (continued).

If  $|u| = 0$ , then word  $v$  starts with an a.

Hence,  $uv^0w = b^{p-|v|+1}ac^{p+2}$  does not start with symbol a and is therefore not in  $L$ . This is a contradiction to the PL.

If  $|u| > 0$ , then word  $v$  consists only of bs.

Consider  $uv^0w = ab^{p-|v|}ac^{p+2}$ . As  $|v| \geq 1$ , this word does not contain two more cs than bs and is therefore not in language  $L$ .

This is a contradiction to the PL.

We have in all cases a contradiction to the PL.

$\rightsquigarrow L$  is not regular. □

## Pumping Lemma: Exercise

This was an exam question in 2020:

Use the pumping lemma to prove that

$L = \{a^m b^n \mid m \geq 0, n < m\}$  is not regular.



## Summary

- ▶ The **pumping lemma** can be used to show that a language is **not regular**.