II.4.1. Regular Grammars and NFAs (13.5)

II.4.2. Translating NFAs into Regular Expressions (13.10)

II.4.3. Equivalence Theorem

II.4.4. Closure Properties and Decidability of Regular Languages

II.4.5. The Pumping Lemma for Regular Languages (12.4, 12.5)
II.4.1. Regular Grammars and NFAs (13.5)

II.4.2. Translating NFAs into Regular Expressions (13.10)

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II.4.4. Closure Properties and Decidability of Regular Languages

II.4.5. The Pumping Lemma for Regular Languages (12.4, 12.5)
Theorem II.4.1.1.

We will show that regular expressions coincide with regular languages and with languages recognised by a DFA or NFA. Here we prove one part of this result:

**Theorem (II.4.1.1.)**

For every right linear grammar $G$ there exists an NFA $A$ s.t.

$$L(G) = L(A)$$

A can be computed from $G$. 

Proof Idea

- A derivation of a word in $G$ has the form

\[
S = A_0 \rightarrow a_1 A_1 \rightarrow a_1 a_2 A_2 \rightarrow \cdots \rightarrow a_1 a_2 \cdots a_{n-1} A_{n-1} \rightarrow a_1 a_2 \cdots a_{n-1} a_n
\]

where we have productions

\[
A_i \rightarrow a_{i+1} A_{i+1} \quad A_{n-1} \rightarrow a_n
\]

or

\[
S = A_0 \rightarrow a_1 A_1 \rightarrow a_1 a_2 A_2 \rightarrow \cdots \rightarrow a_1 a_2 \cdots a_{n-1} A_{n-1} \rightarrow a_1 a_2 \cdots a_{n-1}
\]

where we have productions

\[
A_i \rightarrow a_{i+1} A_{i+1} \quad A_{n-1} \rightarrow \epsilon
\]
Proof Idea

Define $A$ with states $N \cup \{q_F\}$ for a special new accepting state $q_F$ s.t. the derivation

$$S = A_0 \rightarrow a_1 A_1 \rightarrow a_1 a_2 A_2 \rightarrow \cdots \rightarrow a_1 a_2 \cdots a_{n-1} A_{n-1} \rightarrow a_1 a_2 \cdots a_{n-1} a_n$$

corresponds to a sequence of transitions

$$S = A_0 \xrightarrow{a_1} A_1 \xrightarrow{a_2} A_2 \xrightarrow{a_3} \cdots \xrightarrow{a_{n-1}} A_{n-1} \xrightarrow{a_n} q_F$$

and a derivation

$$S = A_0 \rightarrow a_1 A_1 \rightarrow a_1 a_2 A_2 \rightarrow \cdots \rightarrow a_1 a_2 \cdots a_{n-1} A_{n-1} \rightarrow a_1 a_2 \cdots a_{n-1}$$

corresponds to a sequence of transitions

$$S = A_0 \xrightarrow{a_1} A_1 \xrightarrow{a_2} A_2 \xrightarrow{a_3} \cdots \xrightarrow{a_{n-1}} A_{n-1} \in F$$
So we have:

- If \( B \rightarrow aB' \), then \( B \xrightarrow{a} B' \).
- If \( B \rightarrow a \) then \( B \xrightarrow{a} q_F \).
- \( q_F \in F \).
- If \( B \rightarrow \epsilon \), then \( B \in F \).
### Constructed NFA

We obtain from $G = (N, T, S, P)$ the following NFA:

<table>
<thead>
<tr>
<th>automaton</th>
<th>$A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>states</td>
<td>$N \cup {q_F}$</td>
</tr>
<tr>
<td>terminals</td>
<td>$T$</td>
</tr>
<tr>
<td>start</td>
<td>$S$</td>
</tr>
<tr>
<td>final</td>
<td>$B \in N$ s.t. $B \to \epsilon$.</td>
</tr>
<tr>
<td></td>
<td>$q_F$</td>
</tr>
<tr>
<td>transitions</td>
<td>$B \xrightarrow{a} B'$ if $B \to aB'$.</td>
</tr>
<tr>
<td></td>
<td>$B \xrightarrow{a} q_F$ if $B \to a$.</td>
</tr>
</tbody>
</table>
II.4.1. Regular Grammars and NFAs (13.5)

Proof of Theorem II.4.1.1.

Can be found in the additional material.
Example

Consider the Grammar:

<table>
<thead>
<tr>
<th>grammar</th>
<th>$G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>terminals</td>
<td>0, 1</td>
</tr>
<tr>
<td>nonterminals</td>
<td>$S, T$</td>
</tr>
<tr>
<td>start symbol</td>
<td>$S$</td>
</tr>
<tr>
<td>productions</td>
<td>$S \rightarrow 0, S \rightarrow 1T,$ $T \rightarrow 0T, T \rightarrow 1T,$ $T \rightarrow \epsilon, T \rightarrow 0, T \rightarrow 1$</td>
</tr>
</tbody>
</table>
Corresponding Automaton

(Note that it is nondeterministic).
II.4.1. Regular Grammars and NFAs (13.5)

Corresponding Automaton

With corresponding rules:

\[ S \rightarrow 0 \]
\[ S \rightarrow 1 \]
\[ T \rightarrow 1 \]
\[ T \rightarrow 0 \]
\[ T \rightarrow 1 \]

Accepting state because of \[ T \rightarrow \epsilon \]
II.4.1. Regular Grammars and NFAs (13.5)

II.4.2. Translating NFAs into Regular Expressions (13.10)

II.4.3. Equivalence Theorem

II.4.4. Closure Properties and Decidability of Regular Languages

II.4.5. The Pumping Lemma for Regular Languages (12.4, 12.5)
Theorem II.4.2.1.

Let $A = (Q, q_0, F, T, \rightarrow)$ be an NFA. Then there exist a regular expression $E$ s.t. $L(E) = L(A)$. $E$ can be computed from $A$. 
Proof of Theorem II.4.2.1.

A proof of Theorem II.4.2.1. and an example can be found in the additional material.
II.4.3. Equivalence Theorem

II.4.1. Regular Grammars and NFAs (13.5)

II.4.2. Translating NFAs into Regular Expressions (13.10)

II.4.3. Equivalence Theorem

II.4.4. Closure Properties and Decidability of Regular Languages

II.4.5. The Pumping Lemma for Regular Languages (12.4, 12.5)
Theorem II.4.3.1.

Let $L$ be a language over an alphabet $T$. The following are equivalent:

1. $L$ is definable by a regular expression.
2. $L$ is a regular.
3. $L$ is definable by a right-linear grammar.
4. $L$ is definable by a left-linear grammar.
5. $L$ is definable by an NFA with empty moves.
6. $L$ is definable by an NFA.
7. $L$ is definable by a DFA.

Furthermore, the corresponding regular expressions, right linear grammars, left-linear grammars, NFAs with empty moves, NFAs, DFAs can be computed from each other.
II.4.3. Equivalence Theorem

Proof of Theorem II.4.3.1.

A proof of Theorem II.4.3.1. can be found in the additional material.
II.4.1. Regular Grammars and NFAs (13.5)

II.4.2. Translating NFAs into Regular Expressions (13.10)

II.4.3. Equivalence Theorem

II.4.4. Closure Properties and Decidability of Regular Languages

II.4.5. The Pumping Lemma for Regular Languages (12.4, 12.5)
Closure Properties

Theorem (II.4.4.1.)

Regular languages are closed under

1. complement,
2. intersection,
3. the operation $L \mapsto L^R$.

So if $L, L'$ are regular languages over alphabet $T$, so are

1. $L^c$ (the complement of $L$, i.e. $\{t \in T^* \mid t \notin L\}$),
2. $L \cap L'$,
3. $L^R$ (i.e. $\{w^R \mid w \in L\}$, where $w^R$ is the result of reverting $w$).

Furthermore, regular grammars for $L^c$, $L \cap L'$ and $L^R$ can be computed from those for $L$. 
Proof idea for Theorem II.4.4.1.

- We will use that regular expressions, languages definable by DFAs and regular languages are equivalent.
- Languages definable by regular expressions are closed under $L \mapsto L^R$. (See additional material, Lemma II.4.3.4).
- One can easily see that languages definable by a DFA are closed under $L \mapsto L^c$ and under intersection.
- Therefore the assertion follows.
- Full details can be found in the additional material.
Decision Problems

Theorem (II.4.4.3.)

- We can decide for regular languages whether $L = \emptyset$.
- We can decide for regular languages $L$ and $L'$ whether $L \subseteq L'$.
- We can decide for regular languages $L$ and $L'$ whether $L = L'$. 

A proof of Theorem II.4.4.3. can be found in the additional material.
II.4.1. Regular Grammars and NFAs (13.5)

II.4.2. Translating NFAs into Regular Expressions (13.10)

II.4.3. Equivalence Theorem

II.4.4. Closure Properties and Decidability of Regular Languages

II.4.5. The Pumping Lemma for Regular Languages (12.4, 12.5)
Motivation

- We want to show that there are languages which are context-free but not regular.
- In order to do this we prove the pumping lemma, which uses the fact that an NFA has only finitely many states. (We could use as well the fact that a regular grammar has only finitely many nonterminals).

**Note** The following slides contain some coloured parts. The colours are indistinguishable in the black and white handouts. It is recommended to look at them using the online version.

- Reminder on notations:
  \( |u| \) is the length of string \( u \).
  \( uv \) denotes the concatenation of strings \( u \) and \( v \).
Consider an NFA

This NFA has 5 states.
Any run of the NFA for a word of length $\geq 5$ uses at least 6 states.
Therefore it must visit one state at least twice.
So there must be a loop within the first 5 letters of such a word.
Using the Finiteness of an NFA

Here is the run for the word $z = \textbf{a} \textbf{b} \textbf{a} \textbf{b} \textbf{a}$ using colours \textcolor{blue}{blue}, red and \textcolor{green}{green}.

\begin{itemize}
  \item The \textcolor{blue}{blue part} is the part before we reached a state visited twice, corresponding to the word $u = \textbf{a}$.
  \item The \textcolor{red}{red part} is the part from the state visited twice until we reach it again, corresponding to the word $v = \textbf{bab}$.
  \item The \textcolor{green}{green part} is the remaining part, corresponding to the word $w = \textbf{a}$.
  \item The loop must occur within the first 5 letters, so $|uv| \leq 5$. Because $v$ is along a loop, $|v| \geq 1$.
\end{itemize}
II.4.5. The Pumping Lemma for Regular Languages (12.4, 12.5)

Using the Finiteness of an NFA

- If we repeat the loop several times, we obtain as well an accepting word.
  - If we start with $u = a$, then repeat the loop following the word $v = bab$ $i$ times, then the follow the word $w = a$, we obtain an accepting run.
  - It accepts the word $a(bab)^i a$.
    - E.g. in case $i = 2$ the word is $ababbaba$.
    - In case $i = 0$ the word is $aa$.
  - In general we get that the word $uv^i w$ is an element of the language as well.
II.4.5. The Pumping Lemma for Regular Languages (12.4, 12.5)

Generalisation

Assume an NFA $A$ having $k$ states. Then for every word $x \in L(A)$ s.t. $|x| \geq k$ there exist words $u, v, w$ s.t.

$$x = uvw, \quad |uv| \leq k, \quad |v| \geq 1$$

and s.t.

$$uv^i w \in L(A) \text{ for all } i \in \mathbb{N}$$

This follows by the above considerations.

So we have proved the following theorem:
Theorem (Pumping Lemma for Regular Languages)

Let $L$ be a regular language. Then there exist a fixed number $k$ depending on $L$ only s.t. we have the following:

- If $x \in L$ is a word, $|x| \geq k$, then there exist words $u, v, w$ s.t. $x = uvw$, $|uv| \leq k$, $|v| \geq 1$ and s.t.

$$uv^i w \in L(A) \text{ for all } i \in \mathbb{N}$$
Example 1

Lemma

The language $L := \{a^i b^i \mid i \geq 1\}$ is context-free but not regular.
Proof (Example 1)

- We have already seen that $L$ is context-free.
- Assume $L$ is regular.
- Let $k$ be as in the pumping lemma.
- Consider $x := a^k b^k \in L$.
- $|x| \geq k$, so there exist $u, v, w$ s.t.
  $x = uvw$, $|uv| \leq k$, $|v| \geq 1$,
  and s.t.
  $uvw^i w \in L$ for all $i \in \mathbb{N}$.
- Since $|uv| \leq k$, $u$ and $v$ are substrings of $a^k$.
- Therefore $uv^2w = a^{k+l}b^k$ where $l = |v|$.
- But $a^{k+l}b^k \notin L$, a contradiction.
Example 2

Lemma

The language $L := \{xx^R \mid x \in \{a, b\}^*\}$ is context-free but not regular.
Proof (Example 2)

- We have already seen that $L$ is context-free.
- Assume $L$ is regular.
- Let $k$ be as in the pumping lemma.
- Consider $x := a^k b b a^k \in L$.
- $|x| \geq k$, so there exist $u, v, w$ s.t.
  $x = u v w$, $|u v| \leq k$, $|v| \geq 1$,
  and s.t.
  $u v^i w \in L$ for all $i \in \mathbb{N}$.
- Since $|u v| \leq k$, $u$ and $v$ are substrings of $a^k$.
- Therefore $u v^2 w = a^{k+l} b b a^k$ where $l = |v|$.
- But $a^{k+l} b b a^k \notin L$, a contradiction.