Advanced Automata Theory 10
Transducers and Rational Relations

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A structure \((A, R_1, \ldots, R_m, f_1, \ldots, f_n, c_1, \ldots, c_h)\) is automatic iff \(A\) is a regular set and each relation \(R_k\) is an automatic relation with domain \(A^{\ell_k}\) and each function \(f_k\) is an automatic function mapping \(A^{\ell'_k}\) to \(A\); the constants \(c_1, \ldots, c_h\) are specific members of \(A\).

Examples

\((\mathbb{Z}, +, 0)\) is a group with an automatic representation. Indeed, every automatic group in the sense of Khoussainov and Nerode is by definition an automatic structure. \((\mathbb{Q}, +, 0)\) has no automatic representation.
Khoussainov and Nerode showed that whenever in an automatic structure a relation or function is first-order definable from other automatic relations or functions then it is automatic.

\((\mathbb{N}, \times, 0)\) is isomorphic to the structure \((\mathbb{N}, \times)\). The multiplication is not automatic in this structure, hence multiplication cannot be first-order defined from the successor-relation.

If \((A, +, 0)\) is isomorphic to \((\mathbb{N}, +, 0)\) then \(1\) is uniquely determined in \(A\) by the axioms \(1 \neq 0\) and \(\forall x, y [x + y = 1 \Rightarrow x = 0 \lor y = 0]\). Hence one can define the ordering by \(x < y \iff \exists z [x + z + 1 = y]\).
A structure \((A, \oplus, \otimes, 0, 1)\) is called a **semiring with 1** iff it satisfies the following conditions:

1. \((A, \oplus, 0)\) is a commutative monoid;
2. \((A, \otimes, 1)\) is a monoid;
3. \(\forall x, y, z \in A\) \[x \otimes (y \oplus z) = (x \otimes y) \oplus (x \otimes z)\] and \[\forall x, y, z \in A\] \[(x \oplus y) \otimes z = (x \otimes z) \oplus (y \otimes z)\].

If, furthermore, \((A, \oplus, 0)\) is a group then \((A, \oplus, \otimes, 0, 1)\) is called a **ring with 1**.

A semiring / ring is called **commutative** iff \[\forall x, y \ [x \otimes y = y \otimes x]\].
Repetition: Infinite Automatic Ring

Assume that \((F, +, *, 0, 1)\) is a finite ring. Let \(G\) contain those elements \(x_1x_2 \ldots x_n\) in \(F^*\) which either satisfy \(n = 1\) or \(n > 1 \land x_{n-1} \neq x_n\). Intuitively, \(02112\) stands for \(021122222\ldots\) where the last symbol repeats forever.

Now let \(x_1x_2 \ldots x_n + y_1y_2 \ldots y_m = z_1z_2 \ldots z_h\) if for all \(k > 0\), \(x_{\min\{n,k\}} + y_{\min\{m,k\}} = z_{\min\{h,k\}}\). Similarly for multiplication.

Now the member 0 of \(F\) is also the additive neutral element in \(G\) and 1 is also the multiplicative neutral element in \(G\).

The so generated \((G, +, *, 0, 1)\) is an example of an infinite automatic ring and represents the ring of the eventually constant functions \(f : \mathbb{N} \rightarrow F\) with pointwise operations.
Repetition: Partial and Linear Orders

An ordering ⊑ on a set \( A \) is a relation satisfying the following two axioms:

1. \( \forall x, y, z \in A \ [x \sqsubseteq y \land y \sqsubseteq z \Rightarrow x \sqsubseteq z] \);
2. \( \forall x \ [x \not\sqsubseteq x] \).

Well-known automatic orderings are \(<_{\text{lex}}, <_{ll}, <_{\text{sh}} \) and \( \prec \).

An ordering is called linear iff

3. \( \forall x, y \in A \ [x \sqsubseteq y \lor x = y \lor y \sqsubseteq x] \).

The orderings \(<_{\text{lex}} \) and \(<_{ll} \) are linear, the orderings \( <_{\text{sh}} \) and \( \prec \) are not linear.
Cantor designed a way to represent small ordinals as sums of descending chains of $\omega$-powers: $\omega^4 + \omega^2 + \omega^2 + \omega$. Here $\omega^{k+1}$ is the first ordinal which cannot be written as a finite sum of ordinals up to $\omega^k$; $\omega$ is the first ordinal which cannot be written as $1 + 1 + \ldots + 1$.

Write $\omega^3 \cdot 2 + \omega \cdot 3 + 4$ instead of $\omega^3 + \omega^3 + \omega + \omega + \omega + 1 + 1 + 1 + 1 + 1$.

Example to add ordinals:

$$(\omega^8 \cdot 5 + \omega^7 \cdot 2 + \omega^4) + (\omega^7 + \omega^6 + \omega + 1) = \omega^8 \cdot 5 + \omega^7 \cdot 3 + \omega^6 + \omega + 1.$$
Rational Relations

**Automatic Relation**: Finite automaton reads all inputs involved at the same speed with \( \# \) supplied for exhausted inputs.

**Rational Relation**: Nondeterministic finite automaton reads all inputs individually and can read them at different speed.

The first type of automata is called *synchronous*, the second type is called *asynchronous*.

There are many relations which are rational but not automatic.
Formal definition

A rational relation $\mathcal{R} \subseteq (\Sigma^*)^n$ is given by an non-deterministic finite state machine which can process $n$ inputs in parallel and does not need to read them in the same speed. Transitions from one state $p$ to a state $q$ are labelled with an $n$-tuple $(w_1, w_2, \ldots, w_n)$ of words $w_1, w_2, \ldots, w_n \in \Sigma^*$ and the automaton can go along this transition iff for each input $k$ the next $|w_k|$ symbols in the input are exactly those in the string $w_k$ (this condition is void if $w_k = \epsilon$) and in the case that the automaton goes on this transition, $|w_k|$ symbols are read from the $k$-th input word.

A word $(x_1, x_2, \ldots, x_n)$ is in $\mathcal{R}$ iff there is a run of the machine with transitions labelled by $(w_{1,1}, w_{1,2}, \ldots, w_{1,n})$, $(w_{2,1}, w_{2,2}, \ldots, w_{2,n})$, $\ldots$, $(w_{m,1}, w_{m,2}, \ldots, w_{m,n})$ ending up in an accepting state such that $x_1 = w_{1,1}w_{1,2}\ldots w_{1,n}$, $x_2 = w_{2,1}w_{2,2}\ldots w_{m,2}w_{m,1}$, $\ldots$, $x_n = w_{1,n}w_{2,n}w_{m,n}$.
Example 10.2: String Concatenation

Concatenation: $0100 \cdot 1122 = 01001122$; not an automatic relation.

The following automaton witnesses that it is a rational relation over alphabet $\Sigma = \{0, 1, 2\}$.

Sample Run: $(s01, s210, s01210) \Rightarrow (0s1, s210, 0s1210) \Rightarrow (01s, s210, 01s210) \Rightarrow (01q, 2q10, 012q10) \Rightarrow (01q, 21q0, 0121q0) \Rightarrow (01q, 210q, 01210q)$. 
Example 10.3: Subsequence

A string $x$ is a subsequence of $y$ iff it can be obtained from $y$ by deleting symbols at some positions. For example, $12112$ is a subsequence of $010200100102$ and of $1211212$ but not of $321123$.

The following one-state automaton recognises this relation for the binary alphabet $\{0, 1\}$.

$$
\begin{align*}
\text{start} & \rightarrow s \\
(0, 0), (1, 1), (\varepsilon, 0), (\varepsilon, 1)
\end{align*}
$$

In general, there are one initial accepting state $s$ with self-loops from $s$ to $s$ labelled with $(\varepsilon, a)$ and $(a, a)$ for all $a \in \Sigma$.

If $x = 0101$ and $y = 00110011$ then the automaton can accept this subsequence relation $(x, y)$ using transitions labelled $(0, 0), (\varepsilon, 0), (1, 1), (\varepsilon, 1), (0, 0), (\varepsilon, 0), (1, 1), (\varepsilon, 1)$. 

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Example 10.4: Substring

The following automaton recognises the relation of all \((x, y)\) where \(x\) is a nonempty substring of \(y\), that is, \(x \neq \varepsilon\) and \(y = vxw\) for some \(v, w \in \{0, 1\}^*\).

In \(s\): Parsing \((\varepsilon, v)\);
From \(s\) to \(u\): Parsing \((x, x)\);
In \(u\): Parsing \((\varepsilon, w)\).
Exercise 10.5: Rational Relations

Rational relations got their name, as one can use them in order to express relations between the various inputs words which are rational. For example, over alphabet \( \{0\} \), the relation of all \((x, y)\) with \(|x| \geq \frac{2}{3}|y| + 5\) is recognised as follows:

\[(0, \varepsilon), (0, 0), (00, 000)\]

Make automata which recognise the following relations:

(a) \(\{(x, y) \in (0^*, 0^*) : 5 \cdot |x| = 8 \cdot |y|\}\);
(b) \(\{(x, y, z) \in (0^*, 0^*, 0^*) : 2 \cdot |x| = |y| + |z|\}\);
(c) \(\{(x, y, z) \in (0^*, 0^*, 0^*) : 3 \cdot |x| = |y| + |z| \lor |y| = |z|\}\).
Transducers

Transducers are automata recognising rational relations where the first parameter \( x \) is called input and the second parameter \( y \) is called output.

In particular one is interested in transducers computing functions: Two possible runs accepting \((x, y)\) and \((x, z)\) must satisfy \( y = z \). Given \( x \), there is a run accepting some pair \((x, y)\) iff \( x \) is in the domain of the function.

Two main concepts:

**Mealy machines:**
Input/Output pairs on transition-labels.

**Moore machines:**
Input on transition-labels; output in states.
A Mealy machine computing a rational function $f$ is a non-deterministic finite automaton such that each transition is attributed with a pair $(v, w)$ of strings and whenever the machine follows a transition $(p, (v, w), q)$ from state $p$ to state $q$ then one says that the Mealy machine processes the input part $v$ and produces the output part $w$.

Every automatic function is also a rational function and computed by a transducer, but not vice versa.

Mealy machine can compute $\pi$ with $\pi(0) = 0$, $\pi(1) = \varepsilon$, $\pi(2) = \varepsilon$, $\pi(v \cdot w) = \pi(v) \cdot \pi(w)$:

```
start → s
(0, 0), (1, \varepsilon), (2, \varepsilon)
```
Moore machine

Moore machine
Non-deterministic finite automaton such that:
Possibly several starting states and final states;
Transitions \((q, a, p)\) with input symbol \(a \in \Sigma\);
States \(q\) labelled with output string \(w_q \in \Sigma^*\);
Word \(a_1 \ldots a_n\) translated into \(w_{q_0} w_{q_1} \ldots w_{q_n}\) iff \(q_0\) is a
starting state and \(q_n\) is a final state and \((q_m, a_{m+1}, q_{m+1})\) is
a valid transition for all \(m < n\).

Moore machine erasing all 1, 2 and preserving 0 computing
function \(\pi\) with \(\pi(012012) = 00\).
Example: Function $f$

Let $f(a_1a_2 \ldots a_n) = 012a_1a_1a_2a_2 \ldots a_na_n012$, so $f(01) = 0120011012$. Moore machine for $f$:

<table>
<thead>
<tr>
<th>state</th>
<th>starting</th>
<th>acc/rej</th>
<th>output</th>
<th>on 0</th>
<th>on 1</th>
<th>on 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$</td>
<td>yes</td>
<td>rej</td>
<td>012</td>
<td>$p, p'$</td>
<td>$q, q'$</td>
<td>$r, r'$</td>
</tr>
<tr>
<td>$p$</td>
<td>no</td>
<td>rej</td>
<td>00</td>
<td>$p, p'$</td>
<td>$q, q'$</td>
<td>$r, r'$</td>
</tr>
<tr>
<td>$q$</td>
<td>no</td>
<td>rej</td>
<td>11</td>
<td>$p, p'$</td>
<td>$q, q'$</td>
<td>$r, r'$</td>
</tr>
<tr>
<td>$r$</td>
<td>no</td>
<td>rej</td>
<td>22</td>
<td>$p, p'$</td>
<td>$q, q'$</td>
<td>$r, r'$</td>
</tr>
<tr>
<td>$s'$</td>
<td>yes</td>
<td>acc</td>
<td>012012</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$p'$</td>
<td>no</td>
<td>acc</td>
<td>00012</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$q'$</td>
<td>no</td>
<td>acc</td>
<td>11012</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$r'$</td>
<td>no</td>
<td>acc</td>
<td>22012</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Quiz: Write Mealy machine for $f$. 
Example: Function $g$

Let $g(a_1a_2 \ldots a_n) = (\max(\{a_1, a_2, \ldots, a_n\}))^n$. So $g(\varepsilon) = \varepsilon$, $g(000) = 000$, $g(0110) = 1111$ and $g(00212) = 22222$.

Nodes $\{s, q_0, r_0, q_1, r_1, q_2, r_2\}$;
Starting nodes: $s$;
Accepting nodes: $s, r_0, r_1, r_2$.
Output in nodes: $w_s = \varepsilon; w_{q_0} = w_{r_0} = 0; w_{q_1} = w_{r_1} = 1; w_{q_2} = w_{r_2} = 2$.
Transitions: $(s, 0, r_0), (s, 1, r_1), (s, 2, r_2), (s, 0, q_1), (s, 0, q_2), (s, 1, q_2), (r_0, 0, r_0), (q_1, 0, q_1), (q_1, 1, r_1), (r_1, 0, r_1)$, $(r_1, 1, r_1), (q_2, 0, q_2), (q_2, 1, q_2), (q_2, 2, r_2), (r_2, 0, r_2)$, $(r_2, 1, r_2), (r_2, 2, r_2)$.

Quiz: Write a Mealy machine for $g$. 

Determine the minimum number $m$ such that every rational function can be computed by a non-deterministic Moore machine with at most $m$ starting states.

Note that $m$ cannot be 1 as there is a function which maps $\varepsilon$ to 0 and every non-empty word to 1. Give the Moore machine for this function.

Can the same be done to rule out $m = 2$?
Exercise 10.10

A Moore machine / Mealy machine is deterministic, if it has exactly one starting state and each transition reads exactly one input symbol and for each state and each input symbol there is at most one transition which applies.

Make a deterministic Moore machine and a deterministic Mealy machine which do the following with binary inputs: As long as the symbol 1 appears on the input, the symbol is replaced by 0; if at some time the symbol 0 appears, it is replaced by 1 and from then onwards all symbols are copied from the input to the output without any further change.

Examples for input $\rightarrow$ output are $0001 \rightarrow 1001$, $110 \rightarrow 001$, $1111 \rightarrow 0000$, $0 \rightarrow 1$ and $110011 \rightarrow 001011$. 
Exercise 10.11

Let the alphabet be \{0, 1, 2\} and let \( R = \{ (x, y, z, u) : u \) has has \(|x|\) many 0s, \(|y|\) many 1s and \(|z|\) many 2s\}. 

Is \( R \) a rational relation? Prove your result.
Theorem of Nivat

Theorem [Nivat 1968]
Let \(\Sigma_1, \Sigma_2, \ldots, \Sigma_m\) be disjoint alphabets. Let \(\pi_k\) preserve the symbols from \(\Sigma_k\) and erase all other symbols. Now a relation \(R \subseteq \Sigma_1^* \times \Sigma_2^* \times \ldots \times \Sigma_m^*\) is rational iff there is a regular set \(P\) over a sufficiently large alphabet such that 
\[
(w_1, w_2, \ldots, w_n) \in R \iff \exists v \in P [\pi_1(v) = w_1 \land \pi_2(v) = w_2 \land \ldots \land \pi_m(v) = w_m].
\]
Rational Structures

A structure \((A, R_1, R_2, \ldots, R_k, f_1, f_2, \ldots, f_h)\) is rational iff all the \(A\) is regular and \(R_1, R_2, \ldots, R_k\) are rational relations and \(f_1, f_2, \ldots, f_h\) are rational functions.

Furthermore, structures isomorphic to a rational structure might also be called rational.

Every automatic structure is by definition also a rational structure, but not vice versa.

The monoid \((\{0, 1\}^*, \cdot, \varepsilon)\) with \(\cdot\) being the concatenation is a rational structure but not an automatic one.
Theorem of Khoussainov and Nerode

The Theorem of Khoussainov and Nerode does not hold for rational structures.

- There are relations and functions which are first-order definable from rational relations without being a rational relation;
- There is no algorithm to decide whether a given first-order formula in a rational structure is true.

However, certain structures which are not automatic, are still rational.
Exercise 10.13: Random Graph

There is a rational representation of the random graph. Instead of coding $(V, E)$ directly, one first codes a directed graph $(V, F)$ with the following properties:

- For each $x, y \in V$, if $(x, y) \in F$ then $|x| < |y|/2$;
- For each finite $W \subseteq V$ there is a $y$ with $\forall x [(x, y) \in F \iff x \in W]$.

This is done by letting $V = \{00, 01, 10, 11\}^+$ and defining that $(x, y) \in F$ iff there are $n, m, k$ such that $y = a_0b_0a_1b_1 \ldots a_nb_n$ and $a_m = a_k = 0$ and $a_h = 1$ for all $h$ with $m < h < k$ and $x = b_mb_{m+1} \ldots b_{k-1}$. Give a transducer recognising $F$ and show that this $F$ satisfies the two properties above.

Now let $(x, y) \in E \iff (x, y) \in F \lor (y, x) \in F$. Show that $(V, E)$ is the random graph.
Multiplication of Natural Numbers

The multiplicative monoid \((\mathbb{N} - \{0\}, \ast, 1)\) has a rational representation. Here one would represent \(2^{n_1} \cdot 3^{n_2} \cdot \ldots \cdot p_k^{n_k}\) with \(n_k > 0\) by \(0^{n_1} 10^{n_2} 1 \ldots 0^{n_k} 1\) and 1 by \(\varepsilon\).