

Chapter 1

automata abstract

1.1 Finite automata

Definition 1.1 (Finite automaton). A finite automaton (an FA) is a 6-tuple (Q, V, T, E, S, F) where

- Q is a finite set of states,
- V is an alphabet,
- $T \in \mathbb{P}(Q \times V \times Q)$ is a transition relation,
- $E \in \mathbb{P}(Q \times Q)$ is an ε -transition relation
- $S \subseteq Q$ is a set of start states, and
- $F \subseteq Q$ is a set of final states.

□

```
class FA: virtual public FAabs {
    // Q is a finite set of states
    StatePool Q;
    // S is a set of start states, F is a
    // set of final states
    StateSet S, F;
    // Transitions maps each State to its
    // out-transitions.
    TransRel Transitions;
```

```

        // E is the epsilon transition
        relation.
        StateRel E;
    }

```

StatePool: All states in an automaton are allocated from a StatePool. StatePool's can be merged together to form a larger one. (Care must be taken to rename any relations or sets (during merging) that depend on the one StatePool.) State is in $[0, \text{next})$

```

class StatePool {
    int next; // The next one to be
              allocated.
}

```

StateSet: The StateSet is normally associated (implicitly) with a particular StatePool; whenever a StateSet is to interact with another (from a different StatePool), its States must be renamed (to avoid a name clash). The capacity of a StateSet must be explicitly managed; many set operations are not bounds-checked when `assert()` is turned off.

```

class StateSet :protected BitVec {
    // How many States can this set
    contain?
    // [O, domain()) can be contained in
    *this.
    inline int domain() const;

    // set How many States can this set
    contain.
    // [O, r) can be contained in *this.
    inline void set_domain(const int r);
}

class BitVec {

```

```

        // used max number bits in data,
        denote width(domain), [0,
        bits_in_use) ==> [0, width)
    int bits_in_use;
    // number of words, 1, 2, 3, ...
    int words;
    // save bytes of words, [0, 1, 2, ...
    width(domain)]
    unsigned int *data;
}

```

transition relation: $T \in Q \rightarrow \mathbb{P}(V \times Q)$, $T(p) = \{(a, q) | (p, a, q) \in T\}$,
表示状态 p 的 out-transitions. see Fig 1.1

```

// V -> Q
struct TransPair {
    CharRange transition_label;
    State transition_destination;
}
class TransImpl { TransPair *data; }
class Trans: protected TransImpl { }

// map: state(r) -> (T=Trans) out-
// transitions of r
// StateTo::data[r] = out-transitions of
// state r
class TransRel: public StateTo<Trans> {}

// map: state(r) -> T
// data[r] = T
template <class T> class StateTo {
T *data; // 动态数组的index(即状态的index)状
// 态的out-transitions
}

```

```

class FA: virtual public FAabs {
    TransRel Transitions; // maps each State to
                           its out-transitions.
}

```

ε -relation: $E \in \mathbb{P}(Q \times Q) \Rightarrow E \in Q \rightarrow \mathbb{P}(Q), E(p) = \{q \mid (p, q) \in E\}$, 表示 ε 连接状态 p 和状态 q .

```

// Implement binary relations on States. This
// is most often used for epsilon
// transitions.
// map: state(r) -> {StateSet}
// StateTo::data[r] = {StateSet}, 表示状态r与
// {StateSet}的二元关系
class StateRel : protected StateTo<StateSet> {
}

class FA: virtual public FAabs {
    // E is the epsilon transition relation.
    StateRel E;
}

```

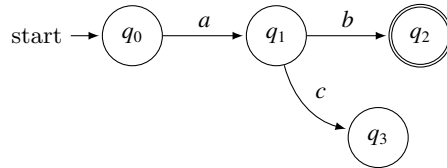


图 1.1: q_1 in-transition: $\{(q_0, a, q_1)\}$; q_1 out-transition: $\{(q_1, b, q_2), (q_1, c, q_3)\}$

[WATSON93a, p6] **the signatures of the transition relations:**

$$T \in \mathbb{P}(Q \times V \times Q)$$

$$T \in V \rightarrow \mathbb{P}(Q \times Q)$$

$$T \in Q \times Q \rightarrow \mathbb{P}(V)$$

$$T \in Q \times V \rightarrow \mathbb{P}(Q)$$

$$T \in \mathcal{Q} \rightarrow \mathbb{P}(V \times \mathcal{Q})$$

for example, the function $T \in \mathcal{Q} \rightarrow \mathbb{P}(V \times \mathcal{Q})$ is defined as $T(p) = \{(a, q) : (p, a, q) \in T\}$

$$T \in \mathbb{P}(\mathcal{Q} \times V \times \mathcal{Q}), T = \{(p, a, q)\}$$

$$T \in \mathcal{Q} \rightarrow \mathbb{P}(V \times \mathcal{Q}), T(p) = \{(a, q) : (p, a, q) \in T\}$$

$$p, q \in \mathcal{Q}, a \in V$$

$$T : \mathcal{Q} \times V \rightarrow \mathbb{P}(\mathcal{Q})$$

$$T(p, a) = \{q\}$$

According to Convention A.4 (Tuple projection):

$$T \in \mathbb{P}(\mathcal{Q} \times V \times \mathcal{Q}), T = \{(p, a, q)\}$$

$$\pi_2(T) = \{a \mid (p, a, q) \in T\}, \bar{\pi}_2(T) = \{(p, q) \mid (p, a, q) \in T\}$$

$$T \in \mathcal{Q} \rightarrow \mathbb{P}(V \times \mathcal{Q}), T(p) = \{(a, q) : (p, a, q) \in T\}$$

$$\pi_2(T(p)) = \{q \mid (p, a, q) \in T\}, \bar{\pi}_2(T(p)) = \{a \mid (p, a, q) \in T\}$$

$$\mathcal{Q}_{map} : \mathcal{Q} \times V, T(p) = \{(a, q) : (p, a, q) \in T\}$$

$$\mathcal{Q}_{map}(q) = \{a\}$$

$$\mathcal{Q}_{map} : \mathcal{Q} \times V, T \in \mathbb{P}(\mathcal{Q} \times V \times \mathcal{Q})$$

$$\pi_1(T) = \{p \mid (p, a, q) \in T\}, \bar{\pi}_1(T) = \{(a, q) \mid (p, a, q) \in T\}$$

$$\mathcal{Q}_{map} = (\bar{\pi}_1(T))^R = \{(a, q) \mid (p, a, q) \in T\}^R = \{(q, a) \mid (p, a, q) \in T\}$$

1.2 Properties of finite automata

$$M = (\mathcal{Q}, V, T, E, S, F), M_0 = (\mathcal{Q}_0, V_0, T_0, E_0, S_0, F_0), M_1 = (\mathcal{Q}_1, V_1, T_1, E_1, S_1, F_1)$$

Definition 1.2 (Size of an FA). Define the size of an FA as $|M| = |\mathcal{Q}|$

Definition 1.3 (Isomorphism 同构 (\cong) of FA's). We define isomorphism (\cong) as an equivalence relation on FA's. M_0 and M_1 are isomorphic (written $M_0 \cong M_1$) if and only if $V_0 = V_1$ and there exists a bijection 双射 $g \in \mathcal{Q}_0 \rightarrow \mathcal{Q}_1$ such that

- $T_1 = \{(g(p), a, g(q)) \mid (p, a, q) \in T_0\}$

- $E_1 = \{(g(p), g(q)) | (p, q) \in E_0\}$
- $S_1 = \{g(s) | s \in S_0\}$ and
- $F_1 = \{g(f) | f \in F_0\}$

(see Fig 1.2). □

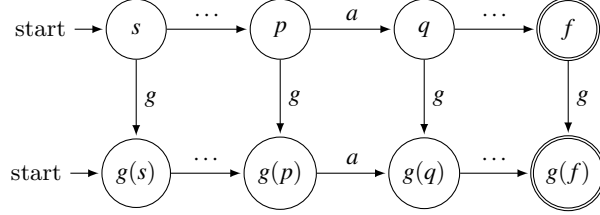


图 1.2: Isomorphism $M_0 \cong M_1$ if and only if $V_0 = V_1$ and there exists a bijection $g \in Q_0 \rightarrow Q_1$

Definition 1.4 (Extending the transition relation T). We extend transition relation $T \in V \rightarrow \mathbb{P}(Q \times Q)$ to $T^* \in V^* \rightarrow \mathbb{P}(Q \times Q)$ as follows:

$$T^*(\varepsilon) = E^*$$

and (for $a \in V, w \in V^*$)

$$T^*(aw) = E^* \circ T(a) \circ T^*(w)$$

Operator \circ (composition is defined in Convention 1).

This definition could also have been presented symmetrically. □

Note 1.1. $s_1, s_2, s_3, s_4 \in Q, a \in V, w \in V^*$

$$E = T(\varepsilon) = \{(s_1, s_2)\}, T(a) = \{(s_2, s_3)\}, T^*(w) = \{(s_3, s_4)\}$$

$$T^*(aw) = E^* \circ T(a) \circ T^*(w)$$

$$= \{(s_1, s_2)\} \circ \{(s_2, s_3)\} \circ \{(s_3, s_4)\} = \{(s_1, s_3)\} \circ \{(s_3, s_4)\} = \{(s_1, s_4)\}$$

Note 1.2. $T \in Q \times V \rightarrow \mathbb{P}(Q)$, extend to: $T^* \in Q \times V^* \rightarrow \mathbb{P}(Q)$

$$\forall q \in Q, w \in V^*, a \in V,$$

1. $T^*(q, \varepsilon) = q$
2. $T^*(q, wa) = T(T^*(q, w), a)$

$$\begin{aligned}
T^*(q, a) &= T^*(q, \varepsilon a) \\
&= T(T^*(q, \varepsilon), a) \\
&= T(q, a)
\end{aligned}$$

两值相同，不用区分这两个符号。

Convention 1 (Relation composition) *Given sets A, B, C (not necessarily different) and two relations, $E \subseteq A \times B$ and $F \subseteq B \times C$, we define relation composition (infix operator 中缀操作符 \circ) as:*

$$E \circ F = \{(a, c) | (\exists b \in B), (a, b) \in E \wedge (b, c) \in F\} \quad \square$$

Note 1.3. if $\exists b \in B, (a, b) \in E, (b, c) \in F$, then

$$E : A \rightarrow B \Rightarrow E(a) = b$$

$$F : B \rightarrow C \Rightarrow F(b) = c$$

$$E \circ F = \{(a, b)\} \circ \{(b, c)\} = \{a, c\}$$

$$\begin{aligned}
(E \circ F)(a) &= F(E(a)) \\
&= F(b) = c
\end{aligned}$$

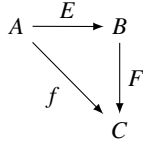


图 1.3: $E \circ F = (F \circ E)(a) = F(E(a)) = c = f(a)$

Remark 1.1. We also sometimes use the signature $T^* \in \mathcal{Q} \times \mathcal{Q} \rightarrow \mathbb{P}(V^*)$ \square

Note 1.4. $T(p, q) = \{w | p, q \in \mathcal{Q}, w \in V^*\}$

Remark 1.2. if $E = \emptyset$ then $E^* = \emptyset^* = I_{\mathcal{Q}}$ where $I_{\mathcal{Q}}$ is the identity relation 单位关系 on the states of M .

Definition 1.5 (The language between states). The language between any two states $q_0, q_1 \in \mathcal{Q}$ is $T^*(q_0, q_1)$. \square

Definition 1.6 (Left and right languages). The left language of a state (in M) is given by function, $\overleftarrow{L}_M \in Q \rightarrow \mathbb{P}(V^*)$, where

$$\overleftarrow{L}_M(q) = (\cup s : s \in S : T^*(s, q))$$

The right language of a state (in M) is given by function $\overrightarrow{L}_M \in Q \rightarrow \mathbb{P}(V^*)$, where

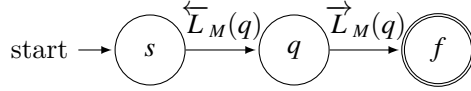
$$\overrightarrow{L}_M(q) = (\cup f : f \in F : T^*(q, f))$$

The subscript M is usually dropped when no ambiguity can arise. \square

Example 1.1. $T^* \in Q \times Q \rightarrow \mathbb{P}(V^*)$, $\overleftarrow{L}_M, \overrightarrow{L}_M \in Q \rightarrow \mathbb{P}(V^*)$.

$\overleftarrow{L}_M(q) = \{\text{能引导 } M \text{ 从开始状态到达 } q \text{ 状态的字符串集合}\}$, (从 q 往左看)

$\overrightarrow{L}_M(q) = \{\text{能引导 } M \text{ 从开始状态到达 } q \text{ 状态的字符串集合}\}$, (从 q 往右看)



see Fig 1.4.

$$\begin{aligned} \overleftarrow{L}_M(q_2) &= (s \rightarrow q_1 \rightarrow q_2) \cup (s \rightarrow (q_1 \rightarrow q_3)^* \rightarrow q_1 \rightarrow q_2) \cup (s \rightarrow (q_1 \rightarrow q_3)^* \rightarrow q_3 \rightarrow q_2) \\ &= [(s \rightarrow q_1 \rightarrow q_2) \cup (s \rightarrow (q_1 \rightarrow q_3)^* \rightarrow q_1 \rightarrow q_2)] \cup (s \rightarrow (q_1 \rightarrow q_3)^* \rightarrow q_3 \rightarrow q_2) \\ &= (s \rightarrow (q_1 \rightarrow q_3)^* \rightarrow q_1 \rightarrow q_2) \cup (s \rightarrow (q_1 \rightarrow q_3)^* \rightarrow q_3 \rightarrow q_2) \\ &= \{1(10)^*0, 1(10)^*1\} \\ \overrightarrow{L}_M(q_2) &= \{01^*0, 10^*1(001^*0 + (10)^*1)\} \end{aligned}$$

Definition 1.7 (Language of an FA). The language of a finite automaton (with alphabet V) is given by the function $L_{FA} \rightarrow \mathbb{P}(V^*)$ defined as:

$L_{FA}(M) = (\cup s, f : s \in S \wedge f \in F : T^*(s, f))$ (所有从开始状态到接受状态的字符串集合) \square

Property 1.1 (Language of an FA). From the definition of left and right languages (of a state), we can also write:

$L_{FA}(M) = (\cup f : f \in F : \overleftarrow{L}(f))$ (所有从 s 到 f 的字符串集合, 从 f 向左看)

and

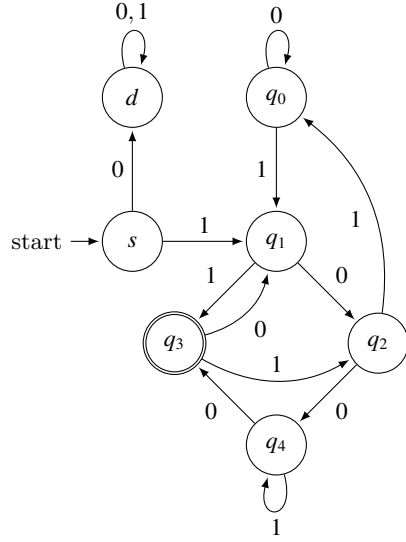


图 1.4: $\{x|x \in \{0,1\}^+ \text{ 且当把 } x \text{ 看成二进制数时, } x \text{ 模 } 5 \text{ 与 } 3 \text{ 同余,}$
 要求当 x 为 0 时, $|x|=1$, 且当 $x \neq 0$ 时, x 的首字符为 1} 语言对应的 DFA

$L_{FA}(M) = (\cup s : s \in S : \vec{L}(s))$ (所有从 s 到 f 的字符串集合, 从 s 向右看) \square

Definition 1.8 (ϵ -free 无 ϵ 转移). Automaton M is ϵ -free if and only if $E = \emptyset$. \square

Remark 1.3. Even if M is ϵ -free it is still possible that $\epsilon \in L_{FA}(M)$: in this case $S \cap F \neq \emptyset$. (开始状态也是接受状态) \square

Form [WATSON93a, Convention A.4] (Tuple projection).

Convention 2 (Tuple projection) For an n -tuple $t = (x_1, x_2, \dots, x_n)$ we use the notation $\pi_i(t) (1 \leq i \leq n)$ to denote tuple element x_i ; we use the notation $\bar{\pi}_i(t) (1 \leq i \leq n)$ to denote the $(n-1)$ -tuple $(x_1, \dots, x_{i-1}, x_{i+1}, \dots, x_n)$. Both π and $\bar{\pi}$ extend naturally to sets of tuples. \square

Form [WATSON93a, Definition A.20] (Tuple and relation reversal).

Definition 1.9 (Tuple and relation reversal). For an n -tuple (x_1, x_2, \dots, x_n) define reversal as (postfix and superscript) function R :

$$(x_1, x_2, \dots, x_n)^R = (x_n, x_{n-1}, \dots, x_1)$$

Given a set A of tuples, we define $A^R = \{x^R : x \in A\}$. \square

Definition 1.10 (Reachable states). For M we can define a reachability relation $Reach(M) \subseteq (Q \times Q)$ defined as

$$Reach(M) = (\bar{\pi}_2(T) \cup E)^* \text{ see}^1$$

Functions π and $\bar{\pi}$ are defined in Convention 2. Similarly the set of start-reachable states is defined to be:

$$SReachable(M) = Reach(M)(S) \text{ see}^2$$

and the set of final-reachable states is defined to be:

$$FReachable(M) = (Reach(M))^R(F) \text{ see}^3$$

Reversal of a relation is defined in Definition 1.9. The set of useful states is: $Reachable(M) = SReachable(M) \cap FReachable(M)$ \square

Remark 1.4. For FA $M = (Q, V, T, E, S, F)$, function $SReachable$ satisfies the following interesting property:

$$q \in SReachable(M) \equiv \overleftarrow{L}_M(q) \neq \emptyset$$

$FReachable$ satisfies a similar property:

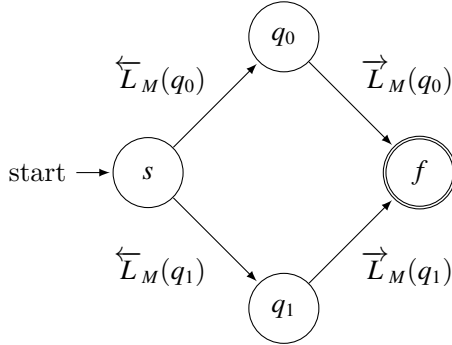
$$q \in FReachable(M) \equiv \overrightarrow{L}_M(q) \neq \emptyset \quad \square$$

Example 1.2. $T \in \mathbb{P}(Q \times V \times Q)$, $T = \{(p, a, q) | p, q \in Q, a \in V\}$,

$$\bar{\pi}_2(T) = \{(p, q) | (p, a, q) \in T\}$$

$$Q_{map} = (\bar{\pi}_1(T))^R, Q_{map} = \{(a, q) | (p, a, q) \in T\}^R = \{(q, a) | (p, a, q) \in T\}$$

\square



¹ $\{(p_1, q_1), (p_2, q_2), \dots\}$

² 从 start state 可以到达的状态集合

³ 可以到达 final state 的状态集合

$$\text{e.g. } p = \{1, 2\} \in Q_1 \subseteq \mathbb{P}(Q_0), \vec{L}_{M_1}(p) = \vec{L}_{M_0}(1) \cup \vec{L}_{M_0}(2)$$

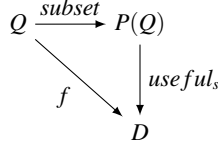


图 1.5: $\text{subset} \circ \text{useful}_s = \text{useful}_s(\text{subset}(Q, V, \emptyset, S, F)) = (D, V, T', \emptyset, S', F')$

1.3 Σ -algebras and regular expressions

Σ -homomorphism

X 集合中的元素与有序集 S 中的元素一一对应, 称 X 是 S -sorted.

$$S = \{1, 3, 7, 9\}, X = \{d, a, c, f\}, s \in S, X_s \in X$$

$$S \text{ 是有序的, } S_{s_1} = 1, S_{s_2} = 3, S_{s_3} = 7, S_{s_4} = 9$$

$$X \text{ 与 } S \text{ 中的元素一一对应。 } X_{s_1} = d, X_{s_2} = a, X_{s_3} = c, X_{s_4} = f$$

Σ -homomorphism 同态: $(V, F) \Leftrightarrow (W, G)$, 载体 (V, W) 和操作 (F, G) 一一对应。

Σ -homomorphism function: $h \in V \rightarrow W$

$$L(v) = (h \circ f)(v) = h(f(v)) = g(w) = L_{reg} = L_V = L_W$$

$$L(v) = (g \circ h)(v) = g(h(v)) = g(w) = L_{reg} = L_V = L_W$$

$$\Rightarrow h(f(v)) = g(h(v))$$

Example 1.3. $\Sigma = (S, \Gamma)$, sort: expr , $\Gamma := \{a, \text{plus}\}$, a is a constant. operator $\text{plus} : \text{expr} \times \text{expr} \rightarrow \text{expr}$.

$$\Sigma\text{-term algebra: } \text{plus}[a, a], \text{plus}[\text{plus}[a, \text{plus}[a, a]], a]$$

Σ -algebra X , carrier set: natural number, constant 0. operator $f_{\text{plus}}(x, y) = (x \max y) + 1$

$$\begin{array}{ccc}
V & \xrightarrow{h} & h(v) \\
f \downarrow & \searrow L & \downarrow g \\
f(v) & \xrightarrow{h} & g(h(v))
\end{array}$$

图 1.6: $(h \circ f)(v) = (g \circ h)(v) \Rightarrow h(f(v)) = g(h(v))$

$$\begin{array}{ccc}
(e_1, e_2) & \xrightarrow{h} & (h(e_1), h(e_2)) \\
f \downarrow & \searrow L & \downarrow g \\
f(e_1, e_2) \circ & \xrightarrow{h} & g(h(e_1), h(e_2))
\end{array}$$

图 1.7: $(h \circ f)(e_1, e_2) = (g \circ h)(e_1, e_2) \Rightarrow h(f(e_1, e_2)) = g(h(e_1), h(e_2))$

Σ -homomorphism function("expression tree height"): $h_{expr} : \Sigma\text{-term algebra} \rightarrow X$

$$\begin{aligned}
(h_{expr} \circ plus)(s) &= (f_{plus} \circ h_{expr})(s) \\
h_{expr}(plus(s)) &= f_{plus}(h_{expr}(s)) \\
left : s \leftarrow e, f &\Rightarrow plus[e, f] \\
right : s \leftarrow e, f &\Rightarrow f_{plus}(h_{expr}(e), h_{expr}(f)) \\
h_{expr}(plus(e, f)) &= f_{plus}(h_{expr}(e), h_{expr}(f)) \\
&= (h_{expr}(e) \max h_{expr}(f)) + 1) \\
&\text{and,} \\
h_{expr}(a) &= 0
\end{aligned}$$

$$\begin{array}{ccc}
S & \xrightarrow{h_{expr}} & X \\
plus \downarrow & \searrow L & \downarrow f_{plus} \\
\circ & \xrightarrow{h_{expr}} & \circ
\end{array}$$

图 1.8: $(h_{expr} \circ plus)(s) = (f_{plus} \circ h_{expr})(s) \Rightarrow h_{expr}(plus(s)) = f_{plus}(h_{expr}(s))$

$$\begin{array}{ccc}
(e, f) & \xrightarrow{h_{\text{expr}}} & (h_{\text{expr}}(e), h_{\text{expr}}(f)) \\
\text{plus} \downarrow & \searrow L & \downarrow f_{\text{plus}} \\
\text{plus}[e, f] & \xrightarrow{h_{\text{expr}}} & f_{\text{plus}}(h_{\text{expr}}(e), h_{\text{expr}}(f))
\end{array}$$

图 1.9: $(h_{\text{expr}} \circ \text{plus})(e, f) = (f_{\text{plus}} \circ h_{\text{expr}})(e, f) \Rightarrow h_{\text{expr}}(\text{plus}[e, f]) = f_{\text{plus}}(h_{\text{expr}}(e), h_{\text{expr}}(f))$

Definition 1.11 (Regular expressions). We define regular expressions (over alphabet V) as the Σ -term algebra over signature $\Sigma = (S, O)$ where

- S consists of a single sort Reg (for regular expression), and
- O is a set of several constans: $\varepsilon, \emptyset, a_1, a_2, \dots, a_n; \text{Reg}$ (where $V = \{a_1, a_2, \dots, a_n\}$) and five operators $\cdot : \text{Reg} \times \text{Reg} \rightarrow \text{Reg}$ (the dot operator), $\cup : \text{Reg} \times \text{Reg} \rightarrow \text{Reg}$, $*$: $\text{Reg} \rightarrow \text{Reg}$, $+$: $\text{Reg} \rightarrow \text{Reg}$, and $?$: $\text{Reg} \rightarrow \text{Reg}$.

$V := RE$ (正则表达式), $W := FA$ (有限自动机)

Σ -homomorphism function: $f \in RE \rightarrow FA$

$F : RE_{\text{opt}}$ 运算, 二元: union(or), concat; 一元: star, plus, question;

常量: epsilon, empty, symbol

$G : FA_{\text{opt}}$ 运算, 同上

$$\begin{array}{ccc}
RE & \xrightarrow{f} & FA \\
\searrow L_{RE} & & \downarrow L_{FA} \\
& & L_{reg}
\end{array}
\qquad
\begin{array}{ccc}
(re_1, re_2) & \xrightarrow{f} & (f(re_1), f(re_2)) \\
RE_{\text{opt}} \downarrow & \searrow & \downarrow FA_{\text{opt}} \\
RE_{\text{opt}}(re_1, re_2) & \xrightarrow{f} & FA_{\text{opt}}(f(re_1), f(re_2))
\end{array}$$

```

//Sigma.h
template<class T>
class Reg : public T {
// Helper for constructing the homomorphic
// image of a regular expression.
// T is carrier set: RE,FA,RFA,
// 各自的操作, 分别在 Sig-RE.cpp, Sig-FA.cpp,
// Sig-RFA.cpp中定义

```

```

inline void homomorphic_image(const RE& r);
Reg<T>& epsilon();
Reg<T>& empty();
Reg<T>& symbol(const CharRange r);
Reg<T>& Or(const Reg<T>& r);
Reg<T>& concat(const Reg<T>& r);
Reg<T>& star();
Reg<T>& plus();
Reg<T>& question();
}

```

Definition 1.12 (The nullable Σ -algebra). We define the *nullable* Σ -algebra as follows:

- The carrier set is $\{true, false\}$.
- $a \in V, E_1, E_2 \in RE, \varepsilon \in E_1^*, \varepsilon \in E_1^?, \varepsilon \notin E_1^+$

$$nullable(\varepsilon) = true$$

$$nullable(\emptyset) = nullable(a) = false$$

$$nullable(E_1 \vee E_2) = nullable(E_1 \cup E_2)$$

$$nullable(E_1 \wedge E_2) = nullable(E_1 \cdot E_2)$$

$$nullable(E_1^*) = true$$

$$nullable(E_1^+) = nullable(E_1)$$

$$nullable(E_1^?) = true$$

$$nullable(E_1) = \begin{cases} true & \varepsilon \in E_1 \\ false & \varepsilon \notin E_1 \end{cases}$$

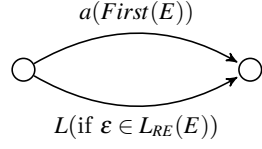


图 1.10: Lookahead function: $look(E, L) = First \cup$ if $(Null(E))$ then L else \emptyset fi

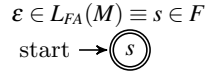


图 1.11: $\varepsilon \in L_{FA}(M) \equiv s \in F$

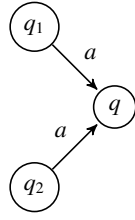


图 1.12: All in-transitions to a state are on the same symbol (in V)

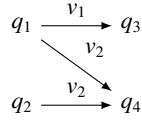


图 1.13: $q_4(in-transition) = \{(q_1, b), (q_2, b)\}, q_1(out-transition) = \{(a, q_3), (b, q_4)\}$

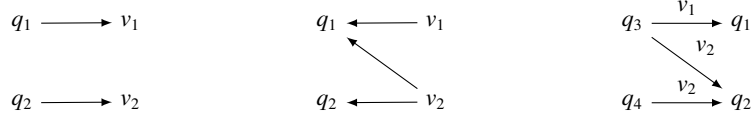
1.4 Constructing ε -lookahead automata

1.5 Towards the Berry-Sethi construction

a	b	c

Definition 1.13 (RFA). A reduced FA (RFA) is a 7-tuple $(Q, V, follow, first, last, null, Q_{map})$ where

- Q is a finite set of states,
- V is an alphabet,



(a) $Q \rightarrow V$ 一一对应关系 (b) $V \rightarrow \mathbb{P}(Q)$ 一对多的关系 (c) 物理含义, 进入状态的字母是唯一的。

$$Q_{map}(q_1) = \{v_1\}, Q_{map}^{-1}(v_1) = \{q_1\}, (q_3, v_1, q_1) \in T$$

$$Q_{map}(q_2) = \{v_2\}, Q_{map}^{-1}(v_2) = \{q_2\}, (q_3, v_2, q_2) \in T, (q_4, v_2, q_2) \in T$$

图 1.14: Q_{map}, Q_{map}^{-1}

- $follow \in \mathbb{P}(Q \times Q)$ is a follow relation (replace the transition relation: $T \in \mathbb{P}(Q \times V \times Q)$),
- $first \subseteq Q$ is a set of initial states (replacing $T(s)$ in an LBFA),
- $null \in \{true, false\}$ is a Boolean value (encoding $s \in F$ in an LBFA, $\varepsilon \in L_{FA}(M) \equiv s \in F$), and
- $Q_{map} \in \mathbb{P}(Q \times V)$, $Q_{map}(q) = \{v\}$, $one \rightarrow one$. maps each state to exactly one symbol. i.e. $Q_{map} \in Q \rightarrow V$.

$Q_{map}(q) = \{a | (p, a, q) \in T\}$ 表示 (q, v) 的一一对应关系。物理含义是进入 q 状态的唯一字母 a

class RFA 中表示 its inverse: $Q_{map}^{-1} : V \rightarrow \mathbb{P}(Q)$, 部分函数 $Q_{map}^{-1}(a) = \{q | (p, a, q) \in T\}$

□

```
class RFA : virtual public FAabs{
// Q is a finite set of states
StatePool Q;

// first(subset Q) is a set of initial states
// (replacing T(s) in an LBFA),
// last(subset Q) is a set of final states,
StateSet first, last;
```



```

// Qmap (in  $P(Q \times V)$ ) maps each state to
// exactly one symbol (it is also viewed as
// Qmap in  $Q \rightarrow V$ ,
// and its inverse as  $Qmap^{-1}$  in  $V \rightarrow P(Q)$ 
// [the set of all partial functions from V
// to  $P(Q)$ ]).
// Trans用struct TransPair 表示:  $T(a) = \{ q \mid$ 
//    $(p, a, q) \in T \}$ ,
// 因此这里表示Qmap的inverse,  $V \rightarrow P(Q)$ 
Trans Qmap_inverse;

// follow (in  $P(Q \times Q)$ ) is a follow relation (
//   replacing the transition relation),
StateRel follow;

// null (in  $\{true, false\}$ ) is a Boolean value
//   (encoding s in F in an LBFA)
// if epsilon属于LBFA, true; final set中包含s
//  $\{true, false\} \Rightarrow \{1, 0\}$ 
int Nullable;
}

```

```

//  $V \rightarrow Q$ 
struct TransPair {
    CharRange transition_label;
    State transition_destination;
}

class TransImpl { TransPair *data; }
class Trans:protected TransImpl { }

}

```

$$rfa \circ R(E) = R \circ rfa(E)$$

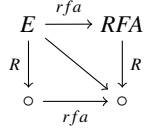


图 1.15: $rfa \circ R(E) = R \circ rfa(E)$

Definition 1.14. (Dual of a function) We assume two sets A and B whose reversal operators are R and R' respectively. Two functions, $f \in A \rightarrow B$ and $f_d \in A \rightarrow B$ are one another's dual if and only if

$$f(a) = (f_d(a^R))^{R'}$$

In some cases we relax the equality to isomorphism (when isomorphism is defined on B). \square

$$f_d \circ R(a) = R' \circ f(a) \Rightarrow f_d(R(a)) = R'(f(a)) \Rightarrow$$

$$f_d(a^R) = (f(a))^{R'} \Rightarrow f(a) = (f_d(a^R))^{R'}$$

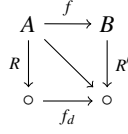


图 1.16: $f(a) = (f_d(a^R))^{R'}$

1.6 The Berry-Sethi construction

Algorithm 2.45(impements *useful*_s \circ *subset*):

initial: $D = \emptyset, U = S$

$$d := \bigcup_{q \in u} T(q, a)$$

$$\{q_1, q_2\} \xrightarrow{a} \{T(q_1, a), T(q_2, a)\}$$

$C_{\cdot, RFA}(rfa(\$), rfa(E)) = C_{\cdot, RFA}(C_{\$, RFA}, rfa(E)) = L_{RE}(\$E) = \{\$ \} L_{RE}(E)$
 $convert$ 简单剔除 E 的第一个字符。 $L_{FA} \circ convert \circ rfa(E) = V^{-1} L_{RE}(E)$
 $convert(C_{\cdot, RFA}(C_{\$, RFA}, rfa(E))) = rfa(E)$

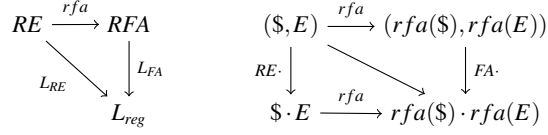


图 1.17: $convert(C_{\cdot, RFA}(C_{\$, RFA}, rfa(E))) = rfa(E)$

using Algorithm 2.45 for $decode(RFA \rightarrow LBFA)$

$$d := \bigcup \{q | q \in first \wedge Q_{map}(q) = a\}$$

$$\{s\} \xrightarrow{a} \{d\}$$

note:

$$d := \bigcup_{p \in u} \{q | (p, q) \in follow \wedge Q_{map}(q) = a\}$$

$$u = \{p_1, p_2\}, d = \{q_1, q_2\},$$

$$follow(p_1) = q_1, follow(p_2) = q_2, Q_{map}(q_1) = Q_{map}(q_2) = a$$

$$\{p_1, p_2\} \xrightarrow{a} \{q_1, q_2\}$$

1.7 The McNaughton-Yamada-Clushkov construction

$$RE \rightarrow [DFA]_{\cong}$$

$$MYG(E) = useful_s \circ subset \circ decode \circ rfa(E)$$

$$\begin{array}{ccccc} RE & \xrightarrow{rfa} & [RFA]_{\cong} & \xrightarrow{decode} & [NFA]_{\cong} \\ & & & & \downarrow subset \\ [DFA]_{\cong} & \xleftarrow{Complete} & [DFA]_{\cong} & \xleftarrow{useful_s} & P(Q) \end{array}$$

图 1.18: $MYG(E) = useful_s \circ subset \circ decode \circ rfa(E)$

1.8 The dual of the Berry-Sethi construction

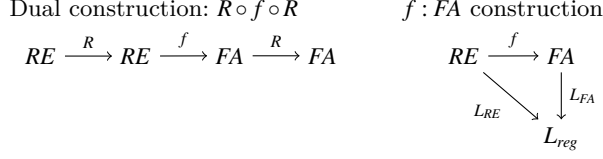


图 1.19: Dual construction: $R \circ f \circ R$

1.9 Others

Definition 1.15 (Prefix-closure[Chrison2007]). Let $L \subseteq V^*$, then

$$\bar{L} := \{s \in V^* : (\exists t \in V^*)[st \in L]\}$$

In words, the prefix closure of L is the language denoted by \bar{L} and consisting of all the prefixes in L . In general, $L \subseteq \bar{L}$.

L is said to be prefix-closed if $L = \bar{L}$. Thus language L is prefix-closed if any prefix of any string in L is also an element of L .

$$L_1 = \{\varepsilon, a, aa\}, \bar{L}_1 = L_1, L_1 \text{ is prefix-closed.}$$

$$L_2 = \{a, b, ab\}, \bar{L}_2 = \{\varepsilon, a, b, ab\}, L_2 \subset \bar{L}_2, L_2 \text{ is not prefix closed.}$$

Definition 1.16 (Post-closure[Chrison2007]). Let $L \subseteq V^*$ and $s \in L$. Then the post-language of L after s , denoted by L/s , is the language

$$L/s := \{t \in V^* : st \in L\}$$

By definition, $L/s = \emptyset$ if $s \notin \bar{L}$.

Definition 1.17 (Left derivatives[WATSON93a]). Given language $A \subseteq V^*$ and $w \in V^*$ we define the left derivative of A with respect to w as:

$$w^{-1}A = \{x \in V^* : wx \in A\}$$

A 关于 w 的左导数, 就是 A 中: $\{w$ 的后缀组成的字符串集合 $\}$ 。

Sometimes derivatives are written as $D_w A$ or as $\frac{dA}{dw}$. Right derivatives are analogously defined. Derivatives can also be extended to $B^{-1}A$ where B is also a language.

Example 1.4. $A = \{a, aab, baa\}$, $a^{-1}A = D_a A = \frac{dA}{da} = \{\varepsilon, ab, \emptyset\} = \{\varepsilon, ab\}$ \square

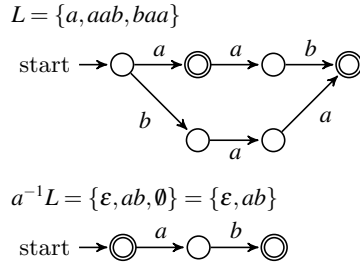


图 1.20: $a^{-1}L$

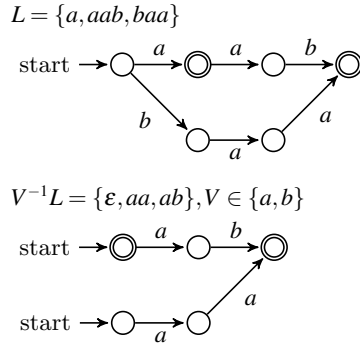


图 1.21: $V^{-1}L$

Example 1.5. $L = \{ba, baa, baab, ca\}$, $w = \{ba\}$,

$$w^{-1}L = \{\varepsilon, a, ab, \emptyset\} = \{\varepsilon, a, ab\}$$

$$(wa)^{-1}L = (baa)^{-1}L = \{\emptyset, \varepsilon, b, \emptyset\} = \{\varepsilon, b\}$$

$$a^{-1}(w^{-1}L) = a^{-1}\{\varepsilon, a, ab\} = \{\emptyset, \varepsilon, b\} = \{\varepsilon, b\}$$

$$w \in L \equiv \varepsilon \in w^{-1}L, \text{ and } (wa)^{-1}L = a^{-1}(w^{-1}L) \quad \square$$

$$\text{Example 1.6. } a^{-1}\{a\} = \{\varepsilon\}; \quad a^{-1}\{b\} = \emptyset, \quad \Leftarrow \text{if } (a \neq b) \quad \square$$

$$\text{Example 1.7. } L_0 = \{ab\}, L_1 = \{ac\}, L_0L_1 = \{abac\}$$

$$\begin{aligned} a^{-1}(L_0L_1) &= \{bac\} \\ a^{-1}(L_0L_1) &= (a^{-1}L_0)L_1 \cup \emptyset \quad \Leftarrow (\varepsilon \notin L_0) \\ &= \{b\}L_1 = \{bac\} \end{aligned} \quad \square$$

$$\text{Example 1.8. } L_0 = \{\varepsilon, ab\}, L_1 = \{ac\}, L_0L_1 = \{ac, abac\}$$

$$\begin{aligned} a^{-1}(L_0L_1) &= \{c, bac\} \\ a^{-1}(L_0L_1) &= (a^{-1}L_0)L_1 \cup a^{-1}L_1 \quad \Leftarrow (\varepsilon \in L_0) \\ &= \{\emptyset, b\}L_1 \cup \{c\} = \{c, bac\} \end{aligned} \quad \square$$

$$\text{证明. } a^{-1}(L_0L_1)$$

$$\begin{aligned} 1. \text{if } (\varepsilon \in L_0) &\Rightarrow a^{-1}(L_0L_1) = (a^{-1}L_0)L_1 \cup a^{-1}L_1 \\ L_0 &= (L_0 \setminus \{\varepsilon\}) \cup \{\varepsilon\} \\ a^{-1}(L_0L_1) &= a^{-1}(((L_0 \setminus \{\varepsilon\}) \cup \{\varepsilon\})L_1) \\ &= a^{-1}(L_0L_1 \cup L_1) \\ a^{-1}L_0 &= a^{-1}((L_0 \setminus \{\varepsilon\}) \cup \{\varepsilon\}) \\ &= a^{-1}(L_0 \setminus \{\varepsilon\}) \cup a^{-1}\{\varepsilon\} \\ &= a^{-1}L_0 \cup \emptyset = a^{-1}L_0 \end{aligned}$$

From [Hopcroft2008, p99]

(1) 如果 L 是一个语言, a 是一个符号, 则 L/a (称作 L 和 a 的商) 是所有满足如下条件的串 w 的集合: wa 属于 L 。例如, 如果 $L = \{a, aab, baa\}$, 则 $L/a = \{\varepsilon, ba\}$, 证明: 如果 L 是正则的, 那么 L/a 也是。提示: 从 L 的 DFA 出发, 考虑接受状态的集合。

(2) 如果 L 是一个语言, a 是一个符号, 则 $a \backslash L$ 是所有满足如下条件的串 w 的集合: aw 属于 L 。例如, 如果 $L = \{a, aab, baa\}$, 则 $a \backslash L = \{\varepsilon, ab\}$, 证明: 如果 L 是正则的, 那么 $a \backslash L$ 也是。提示: 记得正则语言在反转运算下是封闭的, 又由 (1) 知, 正则语言的商运算下是封闭的。

Definition 1.18 (Kleene-closure[Chrison2007]). Let $L \subseteq V^*$, then

$$L^* := \{\varepsilon\} \cup L \cup LL \cup LLL \cup \dots$$

This is the same operation that we defined above for the set V , except that now it is applied to set L whose elements may be strings of length greater than one. An element of L^* is formed by the concatenation of a finite (but possibly arbitrarily large) number of elements of L ; this includes the concatenation of "zero" elements, that is the empty string ε . Note that $*$ operation is idempotent: $(L^*)^* = L^*$.

$$\begin{aligned} L^* &= \{\varepsilon\} + L^+ \\ &= \{\varepsilon\} \cup (L \setminus \{\varepsilon\})L^* \\ &= \{\varepsilon\} + L + LL + LLL + \dots \end{aligned}$$

1.10 Linear equation

see [Jean2018, 5.3,p64].

We give an algorithm to covert an automaton to a rational(regular) expression. The algorithm amounts to solving a system of linear equations on languages. We first consider an equation of the form

$$X = KX + L \tag{1.1}$$

Proposition 1.1 (Arden's Lemma). *if K does not contain the empty word, then $X = K^*L$ is the unique solution of the equation $X = KX + L$.*

where K and L are languages and X is the unknown. When K does not contain the empty word, the equation admits a unique solution.

证明. Replacing X by K^*L in the expression $KX + L$, one gets

$$K(K^*)L + L = K^+L + L = (K^+L + L) = K^*L,$$

and hence $X = K^*L$ is a solution of (1.1). see¹

To Prove uniqueness, consider two solutions X_1 and X_2 of (1.1). By symmetry, it suffices to show that each word u of X_1 also belongs to X_2 . Let us prove this result by induction on the length of u .

If $|u| = 0$, u is the empty word² and if $u \in X_1 = KX_1 + L$, then necessarily $u \in L$ since $\varepsilon \notin K$. But in this case, $u \in KX_2 + L = X_2$. see³

For the induction step, consider a word u of X_1 of length $n + 1$. Since $X_1 = KX_1 + L$, u belongs either to L or to KX_1 . if $u \in L$, then $u \in KX_2 + L = X_2$. If $u \in KX_1$ then $u = kx$ for some $k \in K$ and $x \in X_1$. Since k is not the empty word, one has necessarily $|x| \leq n$ and hence by induction $x \in X_2$. [see⁴] It follows that $u \in KX_2$ and finally $u \in X_2$. This conclude the induction and the proof of the proposition. \square

From [Wonham2018, p74] The *length* $|s|$ of a string $s \in \Sigma^*$ is defined according to

$$|\varepsilon| = 0; |s| = k, \text{ if } s = \sigma_1 \sigma_2 \cdots \sigma_k \in \Sigma^+$$

Thus $|cat(s, t)| = |s| + |t|$.

1

$$\begin{aligned} K^* &= \{\varepsilon\} + K^+ \\ &= \{\varepsilon\} + (K \setminus \{\varepsilon\})K^* \\ &= \{\varepsilon\} + K + KK + KKK + \cdots \end{aligned}$$

² The empty word $= \varepsilon, |\varepsilon| = 0$; if a language $M = \{\varepsilon\}, |M| = 1$, The empty language $M = \emptyset, |M| = 0$. 文献 [Jean2018] 用 1 表示 ε , 因为 $\varepsilon K = K\varepsilon = K$, 因此, ε 是连接运算的单位元, 正是 1 表示的用意。 0 表示 \emptyset , 它是并运算的单位元, $K \cup \emptyset = \emptyset \cup K = K$.

³ In this case, $|u| = 0, X = \{\varepsilon\}, |X| = 1$. i.e. $\varepsilon = K\varepsilon + L, \varepsilon = K + L$

⁴ $u = kx, |u| = |kx| = n + 1, \varepsilon \notin K, |k| \geq 1, |x| \leq n$, 由假设知, u 属于 X_1 , 归纳 $|x| = 0, |x| = 1, \dots, n, x \in X_2$.

A *language* over Σ is any subset of Σ^* , i.e. an element of the power set $Pwr(\Sigma^*)$; thus the definition includes both the empty language \emptyset , and Σ^* itself.

Note the distinction between \emptyset (the language with no strings) and ε (the string with no symbols). For instance the language $\{\varepsilon\}$ is nonempty, but contains only the empty string.

From [Wonham2018, p78]

Proposition 1.2 ([Wonham2018]).

1. If $L = M^*N$ then $L = ML + N$
2. If $\varepsilon \notin M$ then $L = ML + N$ implies $L = M^*N$ □

Part(2) is Known as Arden's rule. Taken with Part(1) it says that if $\varepsilon \notin M$ then $L = M^*N$ is the unique solution of $L = ML + N$; in particular if $L = ML$ (with $\varepsilon \notin M$) then $L = \emptyset$

Exercise 1.1. Show by counterexample that the restriction $\varepsilon \notin M$ in Arden's rule cannot be dropped.

Solution 1.1. Examples text goes here.

Exercise 1.2. Prove Arden's rule. Hint: If $L = ML + N$ then for every $k \geq 0$

$$L = M^{k+1}L + (M^k + M^{k-1} + \cdots + M + \varepsilon)N$$

Solution 1.2.

Preliminaries :

$$M^* = M^k + M^{k-1} + \cdots + M^1 + M^0 \quad (k \geq 0)$$

$$= M^k + M^{k-1} + \cdots + M^1 + \varepsilon$$

$$= M^+ + \varepsilon$$

$$= MM^* + \varepsilon$$

$$= (M \setminus \{\varepsilon\})M^* + \varepsilon$$

$$M^+ = M^k + M^{k-1} + \cdots + M^1 \quad (k > 0)$$

$$= M(M^k + M^{k-1} + \cdots + M^1 + M^0)$$

$$= MM^*$$

$$M^0 = \{\varepsilon\} = 1$$

$$M\varepsilon = \varepsilon M = M$$

$$\varepsilon + \varepsilon = \varepsilon$$

$$M + M = M$$

证明.

$$L = ML + N \Rightarrow$$

$$M^0 L = M^1 L + M^0 N \quad (1.2)$$

$$M^1 L = M^2 L + M^1 N \quad (1.3)$$

$$M^2 L = M^3 L + M^2 N \quad (1.4)$$

$$(1.5)$$

...

\Rightarrow

$$(M^0 + M^1 + M^2 + \cdots)L = (M^1 + M^2 + M^3 + \cdots)L + (M^0 + M^1 + M^2 + \cdots)N$$

\Rightarrow

so, if $L = ML + N$, then for every $k \geq 0$

$$L = M^{k+1}L + (M^k + M^{k-1} + \cdots + M + M^0)N$$

\Rightarrow

$$L = M^{k+1}L + (M^k + M^{k-1} + \cdots + M + \varepsilon)N \quad (1.6)$$

$$(1) k = 0$$

$$L = ML + (\varepsilon)N = ML + N$$

$$\Rightarrow (1 - M)L = N$$

$$(\varepsilon - M)L = N$$

由于 $\varepsilon \notin M$, 左端不会消去 $\{\varepsilon\}$. 因此, 只能在 N 中找 L , 仅有唯一解:

$$L = \{\varepsilon\} = \{\text{empty word}\} \subseteq N.$$

From [R.Su and Wonham2004, definition 2.3]

Definition 1.19. Let

$$G_A = (X_A, \Sigma, \xi_A, x_{A,0}, X_{A,m})$$

$$G_B = (X_B, \Sigma, \xi_B, x_{B,0}, X_{B,m})$$

G_B is a DES-epimorphic image(满射像) of G_A under DES-epimorphism

$\theta : X_A \rightarrow X_B$ if

1. $\theta : X_A \rightarrow X_B$ is surjective(满射)
2. $\theta(x_{A,0}) = x_{B,0}$ and $\theta(X_{A,m}) = X_{B,m}$
3. $(\forall x \in X_A)(\forall \sigma \in \Sigma) \xi_A(x, \sigma)! \Rightarrow [\xi_B(\theta(x), \sigma)! \& \xi_B(\theta(x), \sigma) = \theta(\xi_A(x, \sigma))]$
4. $(\forall x \in X_B)(\forall \sigma \in \Sigma) \xi_B(x, \sigma)! \Rightarrow [(\exists x' \in X_A) \xi_A(x', \sigma)! \& \theta(x') = x]$

In particular, G_B is DES-isomorphic(同构) to G_A if $\theta : X_A \rightarrow X_B$ is bijective(双射).

see figure 1.22.

$$\theta(x_{A,0}) = x_{B,0} \text{ and } \theta(X_{A,m}) = X_{B,m}$$

$$\theta(x_A) = x_B \text{ and } \theta(x'_A) = x'_B$$

$$\xi_A(x_A, \sigma) = x'_A \text{ and } \xi_B(x_B, \sigma) = x'_B \Rightarrow \text{definition 1.19 (3,4)}$$

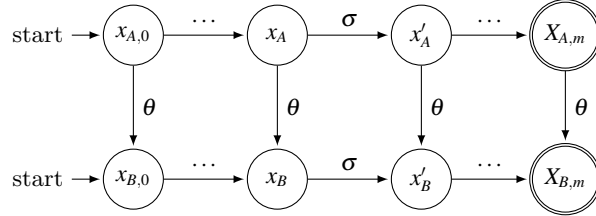


图 1.22: definition 1.19, G_B is a DES-epimorphic image(满射像) of G_A under DES-epimorphism $\theta : X_A \rightarrow X_B$

References

- [Hopcroft2008] John E. Hopcroft, Rajeev Motwani, Jeffrey D. Ullman 著, 孙家骢等译, 自动机理论、语言和计算机导论, Third Edition, 机械工业出版社, 2008.7
- [WATSON93a] WATSON, B. W. *A taxonomy of finite automata construction algorithms*, Computing Science Note 93/43, Eindhoven University of Technology, The Netherlands, 1993. Available by ftp from ftp.win.tue.nl in pub/techreports/pi.
- [WATSON93b] WATSON, B. W. *A taxonomy of finite automata minimization algorithms*, Computing Science Note 93/44, Eindhoven University of Technology, The Netherlands, 1993. Available by ftp from ftp.win.tue.nl in pub/techreports/pi.
- [WATSON94a] WATSON, B. W. *An introduction to the FIRE engine: A C++ toolkit for FInite automata and Regular Expressions*, Computing Science Note 94/21, Eindhoven University of Technology, The Netherlands, 1994. Available by ftp from ftp.win.tue.nl in pub/techreports/pi
- [WATSON94b] WATSON, B.W. *The design. and implementation of the FIRE engine: A C++ toolkit for FInite automata and Regular Expressions*, Computing Science Note 94/22, Eindhoven University of Technology, The Netherlands, 1994. Available by ftp from ftp.win.tue.nl in pub/techreports/pi.
- [Chrison2007] Christos G. Cassandras and Stéphane Lafortune, *Introduction to Discrete Event Systems*, Second Edition, New York, Springer, 2007
- [Wonham2018] W. M. Wonham and Kai Cai, *Supervisory Control of Discrete-Event Systems*, Revised 2018.01.01
- [Jean2018] Jean-Éric Pin, *Mathematical Foundations of Automata Theory*, Version of June 15, 2018
- [蒋宗礼 2013] 蒋宗礼, 姜守旭, 形式语言与自动机理论 (第 3 版), 清华大学出版社, 2013.05
- [Lipschutz2007] S. Lipschutz and M. L. Lipson, *Schaum's Outline of Theory and Problems of Discrete Mathematics*, Third Edition, New York: McGraw-Hill, 2007.
- [Rosen2007] K. H. Rosen, *Discrete Mathematics and Its Applications*, Seventh Edition, New York: McGraw-Hill, 2007.
- [R.Su and Wonham2004] R. Su and W. M. Wonham, *Supervisor reduction for discrete-event systems*, Discrete Event Dyn. Syst., vol. 14, no. 1, pp. 31–53, Jan. 2004.

1. S. MacLane and G. Birkhoff, *Algebra*, Third Edition, New York: Bchelsea Publishing Company, 1988.