Closures

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Closures – example

Example 1

Let A be a set of atomic propositions. The set $PF(A)$ of propositional formulas over A is the least set which fulfills the following properties:

- $a \in PF(A)$, for any $a \in A$ (that is, $A \subseteq PF(A)$);
- if α and β are propositional formulas over A, then

$$\neg\alpha,\ (\alpha \vee \beta),\ (\alpha \wedge \beta),\ (\alpha \Rightarrow \beta),\ \text{and } (\alpha \Leftrightarrow \beta)$$

  are propositional formulas over A.

The three key features of $PF(A)$:

1. "includes A"
2. "closed under" $\neg$, $\vee$, $\wedge$, $\Rightarrow$, $\Leftrightarrow$
3. "least set" with the above properties

Constructors and closures

An n-ary constructor over a set V is a relation r from V^n to V. That is, the elements of r are of the form $((a_1,\ldots,a_n),a)$.

Given an n-ary constructor r and a set A, denote by $r(A)$ the set:

$$r(A) = \{a|(\exists a_1,\ldots,a_n \in A)(((a_1,\ldots,a_n),a) \in r)\}$$

Definition 2

Let A be a set and $\mathcal{R}$ be a set of constructors. The closure of A under $\mathcal{R}$ is the least set $B \subseteq V$ with the properties:

- $A \subseteq B$;
- B is closed under $\mathcal{R}$, i.e., $r(B) \subseteq B$, for any $r \in \mathcal{R}$.

Existence of Closures

Theorem 3 (Existence of closures)

Given a set A and a set $\mathcal{R}$ of constructors, the closure of A under $\mathcal{R}$ exists and it is unique. Moreover, if $\mathcal{R}[A]$ denotes the closure of A under $\mathcal{R}$, then

$$\mathcal{R}[A] = \bigcup_{m \geq 0} B_m,$$

where

- $B_0 = A$;
- $B_{m+1} = B_m \cup \bigcup_{r \in \mathcal{R}} r(B_m)$, *for any* $m \geq 0$;

The closure of A under $\mathcal{R}$ is the union of a chain of sets:

$$B_0 = A, B_1 = B_0 \cup \mathcal{R}(B_0), B_2 = B_1 \cup \mathcal{R}(B_1), \ldots, \bigcup_{m \geq 0} B_m = \mathcal{R}[A],$$

where $\mathcal{R}(B_i) = \bigcup_{r \in \mathcal{R}} r(B_i)$.

The set of natural numbers as a closure

Definition 4

The successor of a set x, denoted $S(x)$, is the set $S(x) = x \cup \{x\}$.

Recall that natural numbers are defined as follows:

- $0 = \emptyset$;
- $1 = S(0) = \{0\} = \{\emptyset\}$;
- $2 = S(1) = \{0, 1\} = \{\emptyset, \{\emptyset\}\}$ etc.

Therefore, $\mathbb{N}$ is the closure of $\{0\}$ under $\mathcal{R} = \{S\}$.

Closures of a binary relation

Definition 5

The reflexive closure of a binary relation $\rho \subseteq A \times A$ is the least reflexive binary relation $r(\rho)$ which includes ρ.

Claim: $r(\rho)$ can be computed as follows:

$$r(\rho) = \rho \cup \iota_A$$

Definition 6

The symmetric closure of a binary relation $\rho \subseteq A \times A$ is the least symmetric binary relation $s(\rho)$ which includes ρ.

Claim: $s(\rho)$ can be computed as follows:

$$s(\rho) = \rho \cup \rho^{-1}$$

Closures of a binary relation

Definition 7

The transitive closure of a binary relation $\rho \subseteq A \times A$ is the least transitive binary relation $t(\rho)$ which includes ρ.

Claim: $t(\rho)$, also denoted by ρ^+, can be computed as follows:

$$t(\rho) = \rho^+ = \bigcup_{m \geq 1} \rho^m,$$

where

- $\rho^1 = \rho$ and
- $\rho^{m+1} = \rho \circ \rho^m$, for all $m \geq 1$.

Closures of a binary relation

Definition 8

The reflexive and transitive closure of a binary relation $\rho \subseteq A \times A$ is the least reflexive and transitive binary relation ρ^* which includes ρ.

Claim: ρ^* can be computed as follows:

$$\rho^* = t(r(\rho)) = r(t(\rho)) = \bigcup_{m \geq 0} \rho^m,$$

where

- $\rho^0 = \iota_A$ and
- $\rho^{m+1} = \rho \circ \rho^m$, for all $m \geq 0$.

Closures of a binary relation

Definition 9

The closure under equivalence of a binary relation $\rho \subseteq A \times A$ is the least equivalence relation $equiv(\rho)$ which includes ρ.

Claim: $equiv(\rho)$ can be computed as follows:

$$equiv(\rho) = t(s(r(\rho))) = t(r(s(\rho))) = r(t(s(\rho))).$$

Remark 1

In general, $s(t(\rho)) \neq t(s(\rho))$.

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Theorem 10 (Structural induction)

Let $B = \mathcal{R}[A]$ be the closure of A under $\mathcal{R}$ and let P be a property such that:

- *$P(a)$, for any $a \in A$;*
- *$(P(a_1) \wedge \cdots \wedge P(a_n) \Rightarrow P(a))$, for any $r \in \mathcal{R}$ and $a_1, \ldots, a_n, a \in B$ with $((a_1, \ldots, a_n), a) \in r$.*

Then, P is satisfied by any $a \in B$.

Remark 2

1. *Structural induction is equivalent to mathematical induction.*
2. *Structural induction is more appropriate for proving properties of closures than mathematical induction.*

Structural induction – example

Example 11

Let A be a set of atomic propositions. The set $PF(A)$ of propositional formulas as defined in Example 1 is the closure of A under some set of constructors (prove it!).

Let $P(\alpha)$ be the following property:

$$P(\alpha): \quad \alpha \text{ has as many left brackets as right brackets.}$$

By structural induction we can easily prove that P is satisfied by all propositional formulas over A (prove it!).

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Definition 12

A set B is inductively defined by A and $\mathcal{R}$ if $B = \mathcal{R}[A]$.

If $B = \mathcal{R}[A]$, then B is obtained as follows:

- $B_0 = A$;
- $B_{m+1} = B_m \cup \mathcal{R}(B_m)$, for all $m \geq 0$;
- $B = \bigcup_{m \geq 0} B_m$.

If the chain

$$B_0, B_1, B_2, \ldots, B_m, B_{m+1} = B_m, B_{m+2} = B_m, \ldots$$

stabilizes to some set B_m, then its union is B_m and, therefore, $B = B_m$.

Definitions by induction

A definition by induction corresponds to the following while-loop (that might be non-terminating):

Algorithm 1: Computing closures

input : set A and set $\mathcal{R}$ of constructors;
output: $B = \mathcal{R}[A]$;

begin
  $B := A$;
  while $\mathcal{R}(B) \not\subseteq B$ **do**
    $B := B \cup \mathcal{R}(B)$

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Definitions by recursion

Assume that B is inductively defined by A and $\mathcal{R}$. It would be a good idea to define functions f on B in a recursive way as follows:

- define f for any $a \in A$;
- if $((a_1, \ldots, a_n), a) \in r$ and the function has already been defined for $a_1, \ldots, a_n$, then define the function for a as a combinations of the values $f(a_1), \ldots, f(a_n)$ in the form

$$h(r)(f(a_1), \ldots, f(a_n)),$$

where h associates a (partial) function $h(r)$ to r.

Definitions by recursion

The definition above has a main drawback: it could not work for some sets B. Just think that the element a above might be defined in at least two different ways,

$$((a_1, \ldots, a_n), a) \in r$$

and

$$((a'_1, \ldots, a'_m), a) \in r'.$$

In such a case, you must be assured that

$$h(r)(f(a_1), \ldots, f(a_n)) = h(r')(f(a'_1), \ldots, f(a'_m)).$$

The easiest way to have this property fulfilled is to ask for each element $a \in B$ to have exactly one inductive construction of it from A and $\mathcal{R}$. If B has this property then it is called a free inductively defined set.

Definitions by recursion

However, for inductively defined sets we can prove the following result:

Lemma 13

Let $B = \mathcal{R}[A]$, C a set, $g : A \to C$, and h a function which associates a partial function $h(r) : C^n \to C$ to each $r \in \mathcal{R}$, where n is the arity of r. Then, there exists a unique relation $f \subseteq B \times C$ such that:

(1) $(a, g(a)) \in f$, *for any* $a \in A$;

(2) *if* $(a_1, b_1), \ldots, (a_n, b_n) \in f$, $((a_1, \ldots, a_n), a) \in r$ *and* $h(r)(b_1, \ldots, b_n)\downarrow$, *then* $(a, h(r)(b_1, \ldots, b_n)) \in f$;

(3) f *is the least relation from* B *to* C *which satisfies (1) and (2).*

Definitions by recursion

Definition 14

A set B is called free inductively defined by A and $\mathcal{R}$ if, for any $a \in B$,

- either $a \in A$,
- or there exists a unique $r \in \mathcal{R}$ and a unique n-tuple $(a_1, \ldots, a_n)$ such that $((a_1, \ldots, a_n), a) \in r$, where n is the arity of r (for $n = 0$ we understand that $a \in r$).

Now, we can obtain the following important result.

Theorem 15 (Recursion theorem)

Let B, C, g, and h as in Lemma 13. If B is free inductively defined by A and $\mathcal{R}$, then the binary relation f from Lemma 13 is a function.

Definitions by recursion

A slight extension of the recursion theorem is the following:

Theorem 16

Let $B = \mathcal{R}[A]$, C a set, $g : A \rightarrow C$, and h a function which associates a partial function $h(r) : B^n \times C^n \rightarrow C$ to each $r \in \mathcal{R}$, where n is the arity of r. If B is free inductively defined by A and $\mathcal{R}$, then there exists a unique function $f : B \rightarrow C$ such that:

(1) $f(a) = g(a)$, *for any* $a \in A$;

(2) $f(a) = h(r)(a_1, \ldots, a_n, f(a_1), \ldots, f(a_n))$, *for any* $a, a_1, \ldots, a_n$ *with* $((a_1, \ldots, a_n), a) \in r$ *and* $h(r)(a_1, \ldots, a_n, f(a_1), \ldots, f(a_{n_r}))\downarrow$, *where* n *is the arity of* r.

Definitions by recursion – example

Example 17

Let $PF(A)$ be the set of propositional formulas over A. It is easy to see that this set is free inductively defined.
Define a function $f : PF(A) \to \mathbb{N}$ in a recursive way as follows:

- $f(a) = 1$, for any $a \in A$;
- $f(\neg\alpha) = f(\alpha)$, for any $\alpha \in PF(A)$;
- $f((\alpha \vee \beta)) = f(\alpha) + f(\beta)$, for any $\alpha, \beta \in PF(A)$;
- $f((\alpha \wedge \beta)) = f(\alpha) + f(\beta)$, for any $\alpha, \beta \in PF(A)$;
- $f((\alpha \Rightarrow \beta)) = f(\alpha) + f(\beta)$, for any $\alpha, \beta \in PF(A)$;
- $f((\alpha \Leftrightarrow \beta)) = f(\alpha) + f(\beta)$, for any $\alpha, \beta \in PF(A)$.

The function f returns the length of propositional formulas.

Definitions by recursion – more examples

Pick up your favorite programming language and:

- show that its set of arithmetic and logic expressions is inductively defined;
- define recursively the length of an arithmetic expression;
- define inductively the set of variables of an arithmetic expression;
- define recursively the "height" of an arithmetic expression.

Definitions by recursion

An important particular case of the recursion theorem:

Theorem 18 (Recursion theorem for $\mathbb{N}$)

Let A be a set, $a \in A$, and $h : \mathbb{N} \times A \to A$ be a function. Then, there exists a unique function $f : \mathbb{N} \to A$ such that:

(1) $f(0) = a$;

(2) $f(n+1) = h(n, f(n))$, *for any* n.

This result can be strengthen to:

Theorem 19 (Parametric recursion theorem for $\mathbb{N}$)

Let A and P be sets, and $g : P \to A$ and $h : P \times \mathbb{N} \times A \to A$ functions. Then, there exists a unique function $f : P \times \mathbb{N} \to A$ such that:

(1) $f(p, 0) = g(p)$, *for any* $p \in P$;

(2) $f(p, n+1) = h(p, n, f(p, n))$, *for any* $p \in P$ *and* $n \in \mathbb{N}$.

Definitions by recursion

Addition, multiplication, and exponentiation on natural numbers are defined by recursion:

- Addition:
  - $x + 0 = x$
  - $x + (n + 1) = (x + n) + 1$;
- Multiplication:
  - $x \cdot 0 = 0$
  - $x \cdot (n + 1) = (x \cdot n) + x$;
- Exponentiation:
  - $x^0 = 1$
  - $x^{n+1} = (x^n) \cdot x$.

Definitions by recursion

In some cases the value of a function f at a natural number n may depend on the values of f at $0, \ldots, n-1$ (Fibonacci's sequence is such an example).
The recursion in such cases is called hereditary.

Theorem 20 (Hereditary recursion theorem)

Let A be a set, $S = \bigcup_{n\in\mathbb{N}} A^n$, and $h : \mathbb{N} \times S \to A$ be a function. Then, there exists a unique function $f : \mathbb{N} \to A$ such that

$$f(n) = h(n, f|_n),$$

for any $n \in \mathbb{N}$ (recall that $f|_0 = f|_\emptyset = \emptyset \in A^0$).

Exercise: Develop a parametric version of the hereditary recursion theorem.

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1. F.L. Țiplea: *Fundamentele Algebrice ale Informaticii*, Ed. Polirom, Iași, 2006, pag. 70–79.

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