

The Z Property

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Abstract

We formalize the Z property introduced by Dehornoy and van Oostrom [1]. First we show that for any abstract rewrite system, Z implies confluence. Then we give two examples of proofs using Z: confluence of lambda-calculus with respect to beta-reduction and confluence of combinatory logic.

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1 The Z property

```
theory Z
imports Abstract-Rewriting.Abstract-Rewriting
begin

locale z-property =
  fixes bullet :: 'a ⇒ 'a (-• [1000] 1000)
  and R :: 'a rel
  assumes Z: (a, b) ∈ R ⇒ (b, a•) ∈ R* ∧ (a•, b•) ∈ R*
begin

lemma monotonicity:
  assumes (a, b) ∈ R*
  shows (a•, b•) ∈ R*
```

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<proof>

lemma *semi-confluence*:

shows $(R^{-1} \circ R^*) \subseteq R^\downarrow$

<proof>

lemma *CR*: $CR\ R$

<proof>

definition $R_d = \{(a, b). (a, b) \in R^* \wedge (b, a^\bullet) \in R^*\}$

end

locale *angle-property* =

fixes *bullet* :: $'a \Rightarrow 'a (-^\bullet [1000] 1000)$

and $R :: 'a\ rel$

and $R_d :: 'a\ rel$

assumes *intermediate*: $R \subseteq R_d\ R_d \subseteq R^*$

and *angle*: $(a, b) \in R_d \implies (b, a^\bullet) \in R_d$

sublocale *angle-property* \subseteq *z-property*

<proof>

sublocale *z-property* \subseteq *angle-property* *bullet* $R\ z\text{-property}.R_d\ \text{bullet}\ R$

<proof>

end

2 Lambda Calculus has the Church-Rosser property

theory *Lambda-Z*

imports

Nominal2.Nominal2

HOL-Eisbach.Eisbach

Z

begin

atom-decl *name*

nominal-datatype *term* =

Var name

| *App term term*

| *Abs x::name t::term binds x in t*

2.1 Ad-hoc methods for nominal-functions over lambda terms

<ML>

method *without-alpha-lst* **methods** *m* =
 (match *termI* in *H* [simproc del: *alpha-lst*]: - \Rightarrow $\langle m \rangle$)

method *Abs-lst* =
 (match **premises** in
 atom ?*x* # *c* and *P* [thin]: [[atom -]]*lst*. - = [[atom -]]*lst*. - for *c* :: 'a::fs \Rightarrow
 \langle rule *Abs-lst1-fcb2'* [where *c* = *c*, OF *P*] \rangle
 | *P* [thin]: [[atom -]]*lst*. - = [[atom -]]*lst*. - \Rightarrow \langle rule *Abs-lst1-fcb2'* [where *c* = (),
 OF *P*] \rangle)

method *pat-comp-aux* =
 (match **premises** in
x = (- :: *term*) \Rightarrow - for *x* \Rightarrow \langle rule *term.strong-exhaust* [where *y* = *x* and *c* =
x] \rangle
 | *x* = (Var -, -) \Rightarrow - for *x* :: - :: *fs* \Rightarrow
 \langle rule *term.strong-exhaust* [where *y* = *fst x* and *c* = *x*] \rangle
 | *x* = (-, Var -) \Rightarrow - for *x* :: - :: *fs* \Rightarrow
 \langle rule *term.strong-exhaust* [where *y* = *snd x* and *c* = *x*] \rangle
 | *x* = (-, -, Var -) \Rightarrow - for *x* :: - :: *fs* \Rightarrow
 \langle rule *term.strong-exhaust* [where *y* = *snd (snd x)* and *c* = *x*] \rangle)

method *pat-comp* = (*pat-comp-aux*; force *simp*: *fresh-star-def fresh-Pair-elim*)

method *freshness* **uses** *fresh* =
 (match **conclusion** in
 - # - \Rightarrow \langle *simp add*: *fresh-Unit fresh-Pair fresh* \rangle
 | - #* - \Rightarrow \langle *simp add*: *fresh-star-def fresh-Unit fresh-Pair fresh* \rangle)

method *solve-eqvt-at* =
 (*simp add*: *eqvt-at-def*; *simp add*: *perm-supp-eq fresh-star-Pair*)+

method *nf* **uses** *fresh* = *without-alpha-lst* (
eqvt-graph-aux, rule *TrueI*, *pat-comp*, *auto*, *Abs-lst*,
auto simp: *Abs-fresh-iff pure-fresh perm-supp-eq*,
freshness fresh: *fresh*)+,
solve-eqvt-at?)

2.2 Substitutions

nominal-function *subst*

where

subst x s (Var *y*) = (if *x* = *y* then *s* else Var *y*)
 | *subst x s* (App *t u*) = App (*subst x s t*) (*subst x s u*)
 | atom *y* # (*x*, *s*) \Rightarrow *subst x s* (Abs *y t*) = Abs *y* (*subst x s t*)
 \langle proof \rangle

nominal-termination (*eqvt*) \langle proof \rangle

lemma *fresh-subst*:

$atom\ z \# s \implies z = y \vee atom\ z \# t \implies atom\ z \# subst\ y\ s\ t$
 ⟨proof⟩

lemma *fresh-subst-id* [simp]:

$atom\ x \# t \implies subst\ x\ s\ t = t$
 ⟨proof⟩

The substitution lemma.

lemma *subst-subst*:

assumes $x \neq y$ **and** $atom\ x \# u$
shows $subst\ y\ u\ (subst\ x\ s\ t) = subst\ x\ (subst\ y\ u\ s)\ (subst\ y\ u\ t)$
 ⟨proof⟩

inductive-set *Beta* ($\{\rightarrow_\beta\}$)

where

$root: atom\ x \# t \implies (App\ (Abs\ x\ s)\ t, subst\ x\ t\ s) \in \{\rightarrow_\beta\}$
 $| Appl: (s, t) \in \{\rightarrow_\beta\} \implies (App\ s\ u, App\ t\ u) \in \{\rightarrow_\beta\}$
 $| Appr: (s, t) \in \{\rightarrow_\beta\} \implies (App\ u\ s, App\ u\ t) \in \{\rightarrow_\beta\}$
 $| Abs: (s, t) \in \{\rightarrow_\beta\} \implies (Abs\ x\ s, Abs\ x\ t) \in \{\rightarrow_\beta\}$

abbreviation *beta* ($(-/ \rightarrow_\beta -)$ [56, 56] 55)

where

$s \rightarrow_\beta t \equiv (s, t) \in \{\rightarrow_\beta\}$

equivariance *Betap*

lemmas *Beta-eqvt* = *Betap.eqvt* [to-set]

nominal-inductive *Betap*

avoids *Abs*: x
 $| root: x$
 ⟨proof⟩

lemmas *Beta-strong-induct* = *Betap.strong-induct* [to-set]

abbreviation *betas* (**infix** \rightarrow_β^* 50)

where

$s \rightarrow_\beta^* t \equiv (s, t) \in \{\rightarrow_\beta\}^*$

nominal-function *app-beta* :: $term \Rightarrow term \Rightarrow term$

where

$atom\ x \# u \implies app\ beta\ (Abs\ x\ s')\ u = subst\ x\ u\ s'$
 $| app\ beta\ (Var\ x)\ u = App\ (Var\ x)\ u$
 $| app\ beta\ (App\ s\ t)\ u = App\ (App\ s\ t)\ u$
 ⟨proof⟩

nominal-termination (*eqvt*) ⟨proof⟩

nominal-function *bullet* :: $term \Rightarrow term$ ($- \bullet$ [1000] 1000)

where

$(Var\ x) \bullet = Var\ x$

$| (Abs\ x\ t)^\bullet = Abs\ x\ t^\bullet$
 $| (App\ s\ t)^\bullet = app\text{-}beta\ s^\bullet\ t^\bullet$
 $\langle proof \rangle$
nominal-termination (*eqvt*) $\langle proof \rangle$

lemma *app-beta-exhaust* [*case-names Redex no-Redex*]:
fixes $c :: 'a :: fs$
assumes $\bigwedge x\ s'.\ atom\ x \# c \implies s = Abs\ x\ s' \implies thesis$
and $(\bigwedge t.\ app\text{-}beta\ s\ t = App\ s\ t) \implies thesis$
shows *thesis*
 $\langle proof \rangle$

lemma *App-Betas*:
assumes $s \rightarrow_{\beta^*} t$ **and** $u \rightarrow_{\beta^*} v$
shows $App\ s\ u \rightarrow_{\beta^*} App\ t\ v$
 $\langle proof \rangle$

lemma *Abs-Betas*:
assumes $s \rightarrow_{\beta^*} t$
shows $Abs\ x\ s \rightarrow_{\beta^*} Abs\ x\ t$
 $\langle proof \rangle$

lemma *self*:
 $t \rightarrow_{\beta^*} t^\bullet$
 $\langle proof \rangle$

lemma *fresh-atom-bullet*:
 $atom\ (x::name) \# t \implies atom\ x \# t^\bullet$
 $\langle proof \rangle$

lemma *subst-Beta*:
assumes $t \rightarrow_{\beta} t'$
shows $subst\ x\ s\ t \rightarrow_{\beta} subst\ x\ s\ t'$
 $\langle proof \rangle$

lemma *Beta-in-subst*:
assumes $s \rightarrow_{\beta} s'$
shows $subst\ x\ s\ t \rightarrow_{\beta^*} subst\ x\ s'\ t$
 $\langle proof \rangle$

lemma *subst-Betas*:
assumes $s \rightarrow_{\beta^*} s'$ **and** $t \rightarrow_{\beta^*} t'$
shows $subst\ x\ s\ t \rightarrow_{\beta^*} subst\ x\ s'\ t'$
 $\langle proof \rangle$

lemma *Beta-fresh*:
fixes $x :: name$
assumes $s \rightarrow_{\beta} t$ **and** $atom\ x \# s$
shows $atom\ x \# t$

<proof>

lemma *Abs-BetaD*:

assumes $Abs\ x\ s \rightarrow_{\beta}\ t$

shows $\exists u. t = Abs\ x\ u \wedge s \rightarrow_{\beta}\ u$

<proof>

lemma *Abs-BetaE*:

assumes $Abs\ x\ s \rightarrow_{\beta}\ t$

obtains u **where** $t = Abs\ x\ u$ **and** $s \rightarrow_{\beta}\ u$

<proof>

lemma *Abs-BetasE*:

assumes $Abs\ x\ s \rightarrow_{\beta^*}\ t$

obtains u **where** $t = Abs\ x\ u$ **and** $s \rightarrow_{\beta^*}\ u$

<proof>

lemma *bullet-App*:

$(App\ s^{\bullet}\ t^{\bullet}, (App\ s\ t)^{\bullet}) \in \{\rightarrow_{\beta}\}^=$

<proof>

lemma *rhs*:

$subst\ x\ s^{\bullet}\ t^{\bullet} \rightarrow_{\beta^*}\ (subst\ x\ s\ t)^{\bullet}$

<proof>

lemma *Betas-fresh*:

fixes $x :: name$

assumes $s \rightarrow_{\beta^*}\ t$ **and** $atom\ x \# s$

shows $atom\ x \# t$

<proof>

lemma *Var-BetaD*:

assumes $Var\ x \rightarrow_{\beta}\ t$

shows *False*

<proof>

lemma *Var-BetasD*:

assumes $Var\ x \rightarrow_{\beta^*}\ t$

shows $t = Var\ x$

<proof>

lemma *app-beta-Betas*:

assumes $s \rightarrow_{\beta^*}\ s'$ **and** $t \rightarrow_{\beta^*}\ t'$

shows $app\ beta\ s\ t \rightarrow_{\beta^*}\ app\ beta\ s'\ t'$

<proof>

lemma *lambda-Z*:

assumes $s \rightarrow_{\beta}\ t$

shows $t \rightarrow_{\beta^*}\ s^{\bullet} \wedge s^{\bullet} \rightarrow_{\beta^*}\ t^{\bullet}$

<proof>

interpretation *lambda-z: z-property* *bullet Beta*

<proof>

end

3 Combinatory Logic has the Church-Rosser property

theory *CL-Z* **imports** *Z*

begin

datatype *CL* = *S* | *K* | *I* | *App* *CL* *CL* (*' - - [999, 999] 999*)

inductive-set *red* :: *CL* *rel* **where**

L: $(t, t') \in \text{red} \implies (' t u, ' t' u) \in \text{red}$
| *R*: $(u, u') \in \text{red} \implies (' t u, ' t u') \in \text{red}$
| *S*: $((' ' S x y z, ' ' x z ' y z) \in \text{red}$
| *K*: $((' ' K x y, x) \in \text{red}$
| *I*: $((' I x, x) \in \text{red}$

lemma *App-mono*:

$(t, t') \in \text{red}^* \implies (u, u') \in \text{red}^* \implies (' t u, ' t' u') \in \text{red}^*$
<proof>

fun *bullet-app* :: *CL* \Rightarrow *CL* \Rightarrow *CL* **where**

bullet-app (*' ' S* *x y*) *z* = *' ' x z ' y z*
| *bullet-app* (*' K* *x*) *y* = *x*
| *bullet-app* *I* *x* = *x*
| *bullet-app* *t u* = *' t u*

lemma *bullet-app-red*:

$((' t u, \text{bullet-app } t u) \in \text{red}^=$
<proof>

lemma *bullet-app-redsI*:

$(s, ' t u) \in \text{red}^* \implies (s, \text{bullet-app } t u) \in \text{red}^*$
<proof>

lemma *bullet-app-redL*:

$(t, t') \in \text{red} \implies (\text{bullet-app } t u, \text{bullet-app } t' u) \in \text{red}^*$
<proof>

lemma *bullet-app-redR*:

$(u, u') \in \text{red} \implies (\text{bullet-app } t u, \text{bullet-app } t u') \in \text{red}^*$
<proof>

```

lemma bullet-app-mono:
  assumes  $(t, t') \in \text{red}^*$   $(u, u') \in \text{red}^*$  shows  $(\text{bullet-app } t \ u, \text{bullet-app } t' \ u') \in \text{red}^*$ 
  <proof>

fun bullet ::  $CL \Rightarrow CL$  where
  bullet ('  $t \ u$ ) = bullet-app (bullet  $t$ ) (bullet  $u$ )
  | bullet  $t$  =  $t$ 

lemma bullet-incremental:
   $(t, \text{bullet } t) \in \text{red}^*$ 
  <proof>

interpretation CL:z-property bullet red
  <proof>

lemmas  $CR\text{-red} = CL.CR$ 

end

```

References

- [1] P. Dehornoy and V. v. Oostrom. Z, proving confluence by monotonic single-step upperbound functions. In *Logical Models of Reasoning and Computation (LMRC'2008)*, 2008.