

# The Architecture of core.logic

Clojure/West 2013

## Connecting the Wires



A goal  $g$  is a function that maps a substitution  $s$  to an ordered sequence  $s^*$  of zero or more substitutions. (For clarity, we notate lambda as  $\lambda_s$  when creating such a function  $g$ .) Because the sequence of substitutions may be infinite, we represent it not as a list but a stream. Streams contain either zero, one, or more substitutions.<sup>1</sup> We use (mzero) to represent the empty stream of substitutions. For example, #s maps every substitution to (mzero). If  $s$  is a substitution, then (unit  $s$ ) represents the stream containing just  $s$ . For instance, #s maps every substitution  $s$  to just (unit  $s$ ). The goal created by an invocation of the  $\pi$  operator maps a substitution  $s$  to either (mzero) or to a stream containing a single (possibly extended) substitution, depending on whether that goal fails or succeeds. To represent a stream containing multiple substitutions, we use (choice  $s$ ), where  $s$  is the first substitution in the stream, and where  $f$  is a function of zero arguments. Invoking the function  $f$  produces the remainder of the stream, which may or may not be empty. (For clarity, we notate lambda as  $\lambda_s$  when creating such a function  $f$ .)

When we use the variable  $s$  rather than  $s'$  for substitutions, it is to emphasize that this representation of streams works for other kinds of data, as long as a datum is never #f or a pair whose cdr is a function—in other words, as long as the three cases above are never represented in overlapping ways. To discriminate among the cases we define the macro case<sup>2</sup>.

The second case is redundant in this representation: (unit  $s$ ) can be represented as (choice  $s$  ( $\lambda_s$  () #f)). We include unit, which avoids building and taking apart pairs and invoking functions, because many goals never return multiple substitutions. run inserts a stream of substitutions  $s^*$  to a list of values using map<sup>3</sup>.

Two streams can be merged either by concatenating them using nplus (also known as stream-append) or by interleaving them using mplus<sup>4</sup>. The only difference between the definitions nplus and mplus<sup>5</sup> lies in the recursive case: nplus<sup>6</sup> swaps the two values in  $s^*$  to the goal  $g$  to get a new stream, then merge all these new streams together using either nplus or mplus<sup>7</sup>. When using nplus, this operation is called monadic<sup>8</sup> bind, and it is used to implement the fair conjunction all<sup>9</sup>. The operators all and all<sup>10</sup> are like and, since they are short-circuiting: the false value short-circuits and, and any failed goal short-circuits all and all<sup>11</sup>. Also, the let in the third clause of all-aux ensures that (all  $s$ ), (all  $e$ ), (all  $e$  #s), and (all  $e$  #s) are equivalent to  $e$ , even if the expression  $e$  has no value. The addition of the superfluous second clause allows all-aux expressions to expand to simpler code.

To take the disjunction of goals we define cond<sup>12</sup>, and to take the fair disjunction we define cond<sup>13</sup>. They combine successive question-answer lines using nplus and mplus<sup>14</sup>, respectively. Two stranger kinds of disjunction are cond\* and cond\*. When a question  $q$  succeeds, both cond\* and cond\* skip the remaining lines. However, cond\* chops off every substitution after the first produced by  $q$ , whereas cond\* leaves the stream produced by  $q$  intact.

<sup>1</sup>See Philip L. Wadler, How to replace failure by a list of successes: a method for exception handling, backtracking, and pattern matching in lazy functional languages. *Functional Programming Languages and Computer Architecture*, Lecture Notes in Computer Science 201, Springer, pages 115–128. J. Michael Spivey and Steve Berry, *Contributions to logic programming: The Fun of Programming*, Palgrave, and Mitchell Wand and Dale VanDerWeert, *Relating Models of Backtracking*, Ninth International Conference on Functional Programming, 2004, pages 54–65.

<sup>2</sup>See Eugenio Moggi, Notions of computation and monads, *Information and Computation* 83(2):55–95, 1990; Philip L. Wadler, The essence of functional programming, *Ninth Annual Symposium on Principles of Programming Languages*, 1992, pages 1–14; and Ralf Hinze, Deriving backtracking monad transformers, *Fifth International Conference on Functional Programming*, 2000, pages 198–217.

# Scheme

```
(define-syntax case-inf
  (syntax-rules ()
    ((_ e (( e0) ((f^ e1) ((c^ e2) ((c f) e3)))
      (let ((c-inf e))
        (cond
          ((not c-inf) e0)
          ((procedure? c-inf) (let ((f^ c-inf)) e1))
          ((not (and (pair? c-inf)
                     (procedure? (cdr c-inf))))
           (let ((c^ c-inf)) e2))
          (else (let ((c (car c-inf)) (f (cdr c-inf)))
                   e3)))))))

(define bind
  (lambda (c-inf g)
    (case-inf c-inf
      (() (mzero))
      ((f) (inc (bind (f) g)))
      ((c) (g c))
      ((c f) (mplus (g c) (lambdaf@ () (bind (f) g)))))))

(define mplus
  (lambda (c-inf f)
    (case-inf c-inf
      (() (f))
      ((f^ (inc (mplus (f) f^)))
      ((c) (choice c f))
      ((c f^ (choice c (lambdaf@ () (mplus (f) f^)))))))

(define take
  (lambda (n f)
    (cond
      ((and n (zero? n)) '())
      (else
       (case-inf (f)
         (() '())
         ((f) (take n f))
         ((c) (cons c '()))
         ((c f) (cons c (take (and n (- n 1)) f)))))))))
```

# Clojure

```
(deftype Substitutions [...]
  ...
  IBind
  (bind [this g]
    (g this))
  IMPlus
  (mplus [this f]
    (choice this f))
  ITake
  (take* [this] this))

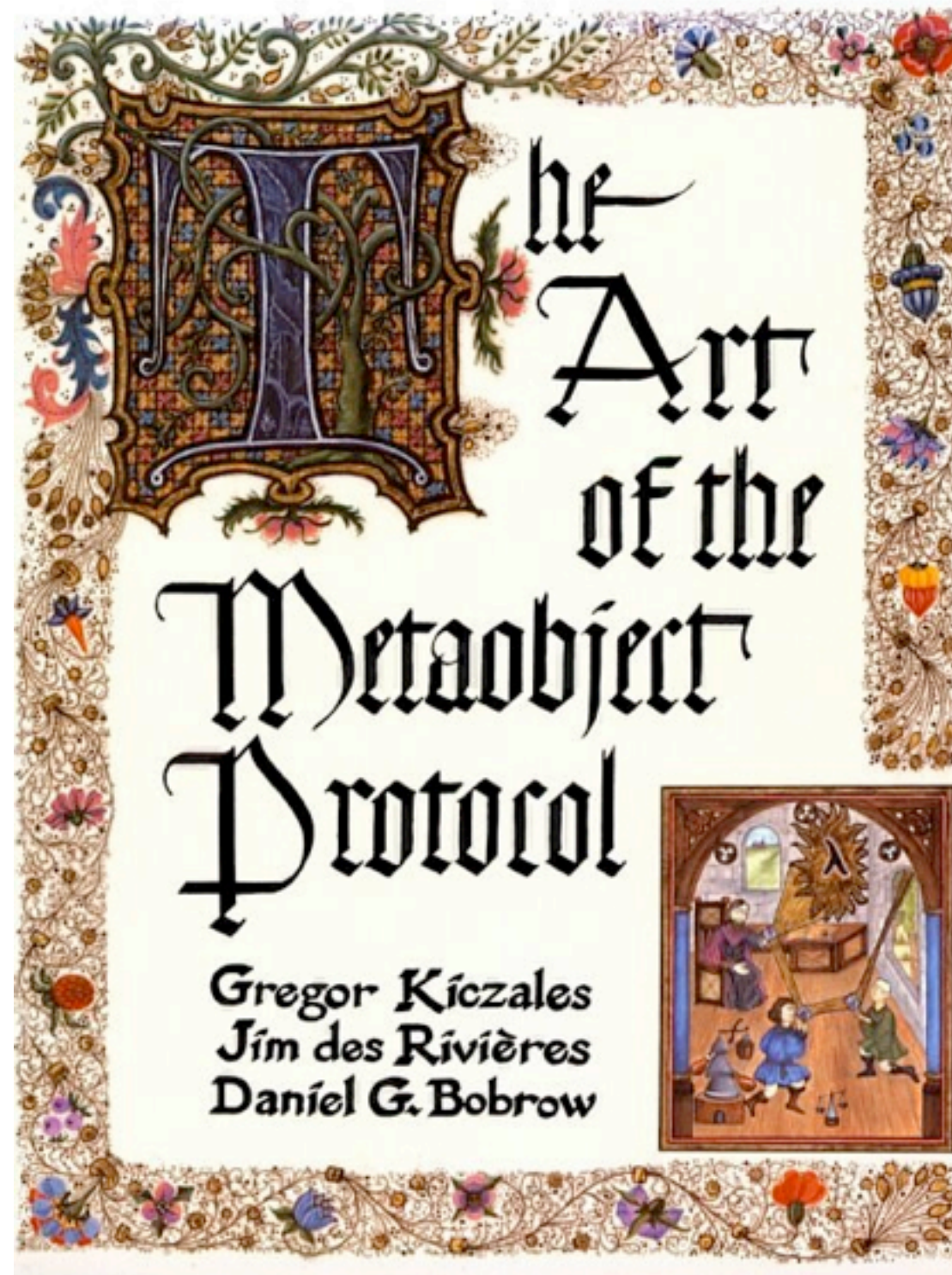
(deftype Choice [a f]
  clojure.lang.ILookup
  (valAt [this k]
    (.valAt this k nil))
  (valAt [this k not-found]
    (case k
      :a a
      not-found))
  IBind
  (bind [this g]
    (mplus (g a) (fn [] (bind f g))))
  IMPlus
  (mplus [this fp]
    (Choice. a (fn [] (mplus (fp) f))))
  ITake
  (take* [this]
    (lazy-seq (cons (first a) (lazy-seq (take* f))))))

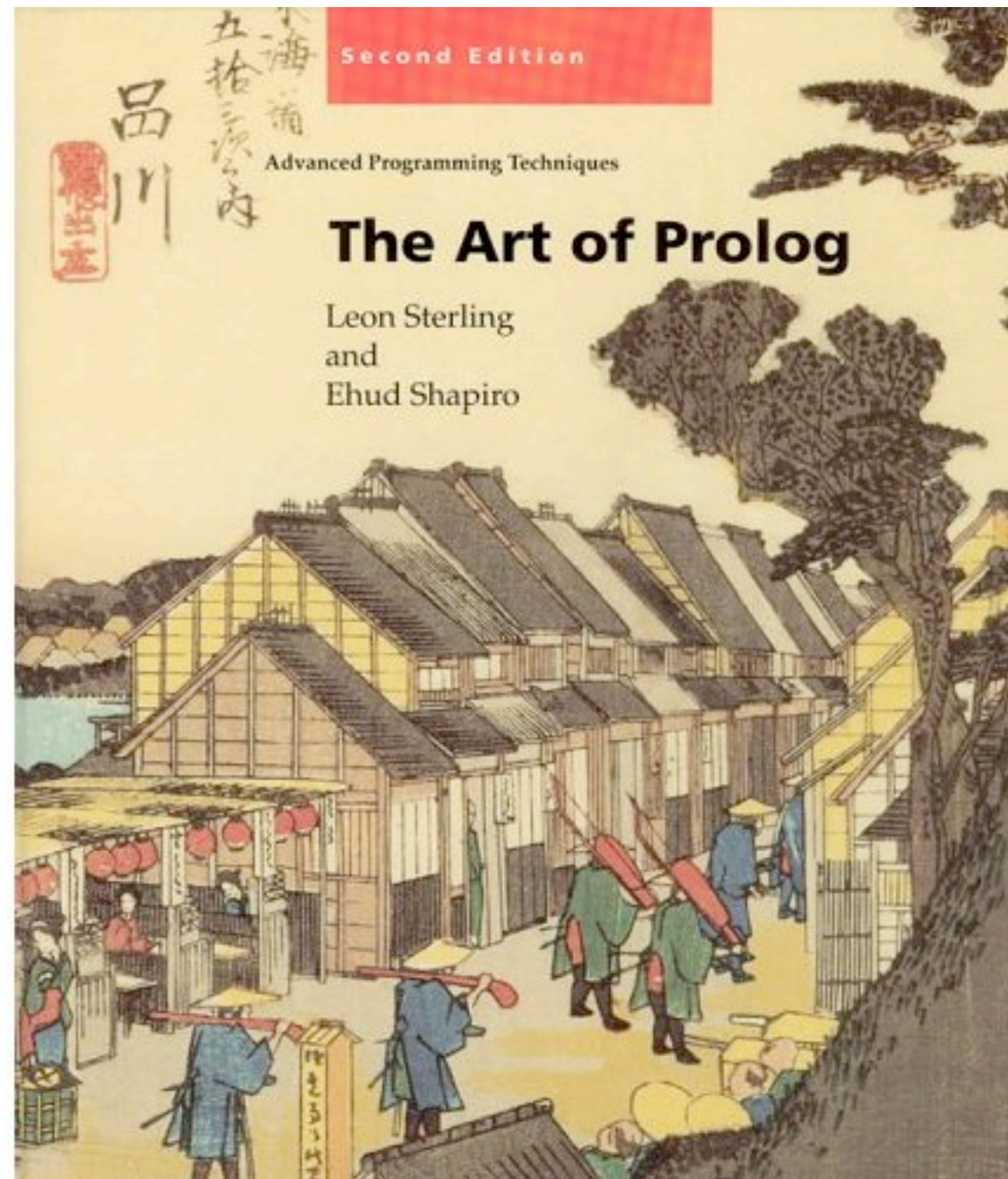
(extend-type nil
  IBind
  (bind [_ g] nil)
  IMPlus
  (mplus [_ f] (f))
  ITake
  (take* [_] '()))

(extend-type Object
  IMPlus
  (mplus [this f]
    (Choice. this f)))

(extend-type clojure.lang.Fn
  IBind
  (bind [this g]
    (-inc (bind (this) g)))
  IMPlus
  (mplus [this f]
    (-inc (mplus (f) this)))
  ITake
  (take* [this] (lazy-seq (take* (this)))))
```







*... An exciting development within logic programming has been the realization that unification is just one instance of constraint solving ...*

# cKanren



# cKanren

- Claire Alvis, William Byrd, Dan Friedman, et al Scheme Workshop 2011

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- Claire Alvis, William Byrd, Dan Friedman, et al Scheme Workshop 2011
- miniKanren extended to CLP(FD) & CLP(Tree)



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- Claire Alvis, William Byrd, Dan Friedman, et al Scheme Workshop 2011
- miniKanren extended to CLP(FD) & CLP(Tree)
- big idea - different constraint solvers should work well together!

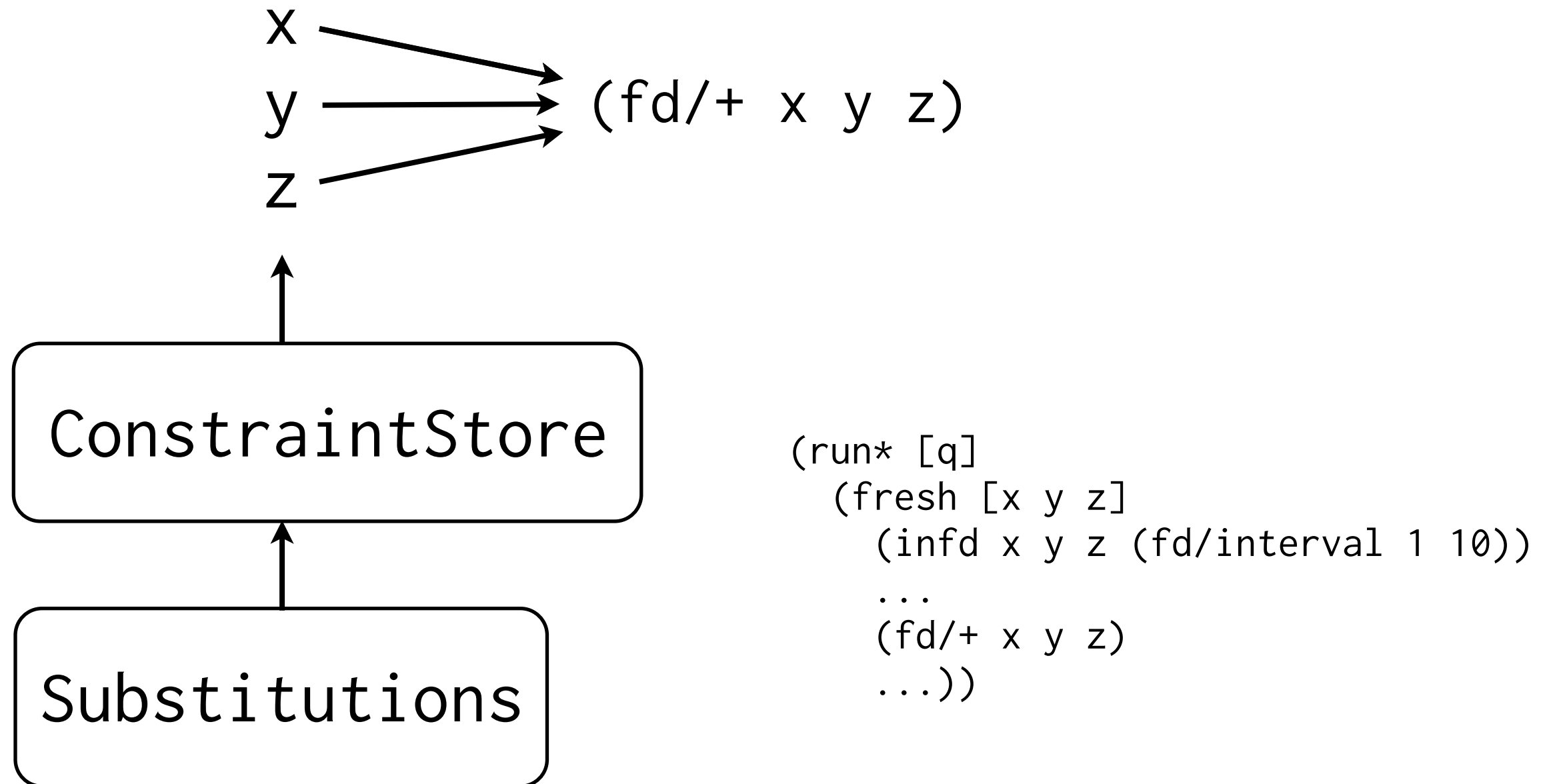


ConstraintStore

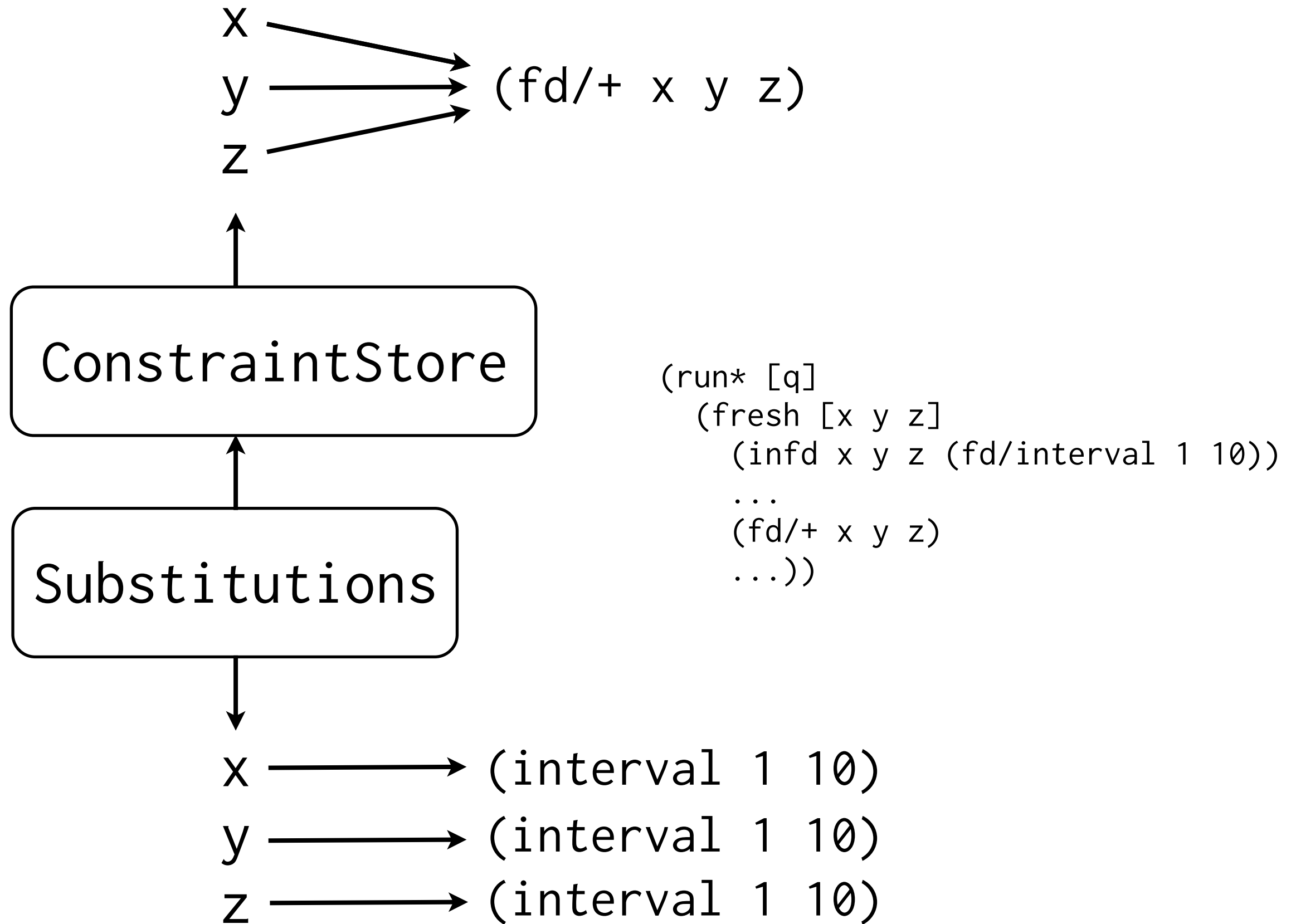


Substitutions

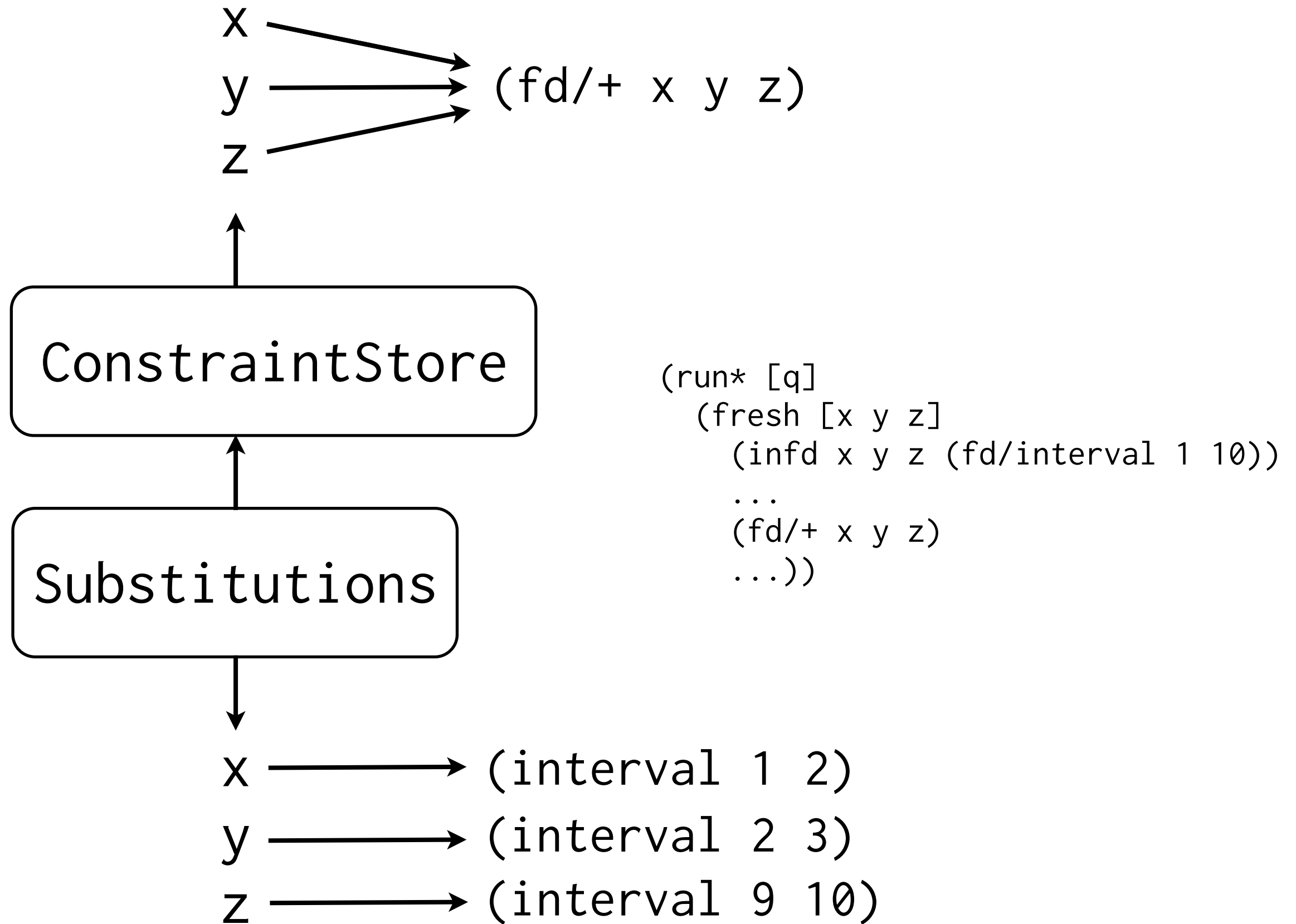
```
(run* [q]
  (fresh [x y z]
    (infd x y z (fd/interval 1 10))
    ...
    (fd/+ x y z)
    ...))
```



```
(run* [q]
  (fresh [x y z]
    (infd x y z (fd/interval 1 10))
    ...
    (fd/+ x y z)
    ...))
```







```
(define empty-s ())
```

```
(deftype Substitutions [s vs ts cs cq cqs oc _meta])
```

substitutions (PersistentHashMap)



[s vs ts cs cq cqs oc \_meta]

vars altered during unification  
(Persistent Vector)



[s vs ts cs cq cqs oc \_meta]



goal tables

(mutable atom w/ PersistentHashMap)



[s vs ts cs cq cqs oc \_meta]

Constraint Store  
(custom deftype)



[s vs ts cs cq cqs oc \_meta]

# Constraint Queue (Persistent Vector)



```
[s vs ts cs cq cqs oc _meta]
```

# Constraint Queue Set (Persistent Vector)



[s vs ts cs cq cqs oc \_meta]

Occurs check flag  
(boolean)



[s vs ts cs cq cqs oc \_meta]



```
(deftype ConstraintStore [km cm cid running])
```

var  $\rightarrow$  constraint id set  
(PersistentHashMap)



[km cm cid running]

constraint id  $\rightarrow$  constraint  
(PersistentHashMap)



[km cm cid running]

constraint id counter  
(long)



[km cm cid running]

running constraint id  
(long)



[km cm cid running]



```
(deftype ConstraintStore [km cm cid running]
  ...
  IConstraintStore
  (addc [this a c] ...)
  (updatec [this a c] ...)
  (remc [this a c] ...)
  (runc [this c state] ...)
  (constraints-for [this a x ws] ...)
  (migrate [this x root] ...))
```

```
(deftype ConstraintStore [km cm cid running]
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```





S E N D  
+ M O R E  
-----  
M O N E Y



- Implementation in the cKanren paper uses long addition to solve efficiently

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- Most users will not want to formulate their equations in this way

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- Most users will not want to formulate their equations in this way
- I tried to write it in a more natural representation



```

(define cryptarithfd
  (lambda ()
    (run 1 (q)
      (fresh (s e n d m o r y
              p0 p1 p2 p3 p4 p5 p6 p7 p8 p9
              s0 s1 s2 s3 s4 s5 s6 s7 s8 s9 s10)
        (== q `(:,s ,e ,n ,d ,m ,o ,r ,y))
        (infd s e n d m o r y (range 0 9))
        (infd p0 p3 p7 (range 0 9000))
        (infd p1 p4 p8 (range 0 900))
        (infd p2 p5 p9 (range 0 90))
        (infd p6 (range 0 90000))
        (infd s0 (range 0 9900))
        (infd s1 (range 0 9990))
        (infd s2 (range 0 9999))
        (infd s3 (range 0 18999))
        (infd s4 (range 0 19899))
        (infd s5 (range 0 19989))
        (infd s6 (range 0 19998))
        (infd s7 (range 0 99000))
        (infd s8 (range 0 99900))
        (infd s9 (range 0 99990))
        (infd s10 (range 0 99999))
        (distinctfd q)
        (=/=fd m 0) (=/=fd s 0)
        (timesfd 1000 s p0) (timesfd 100 e p1) (timesfd 10 n p2)
        (timesfd 1000 m p3) (timesfd 100 o p4) (timesfd 10 r p5)
        (timesfd 10000 m p6) (timesfd 1000 o p7) (timesfd 100 n p8) (timesfd 10 e p9)
        (plusfd p0 p1 s0) (plusfd s0 p2 s1) (plusfd s1 d s2)
        (plusfd s2 p3 s3) (plusfd s3 p4 s4) (plusfd s4 p5 s5) (plusfd s5 e s6)
        (plusfd p6 p7 s7) (plusfd s7 p8 s8) (plusfd s8 p9 s9) (plusfd s9 y s10)
        (=fd s6 s10))))))

```

>42 seconds (Petite Chez)

# Concepts, Techniques, and Models of Computer Programming

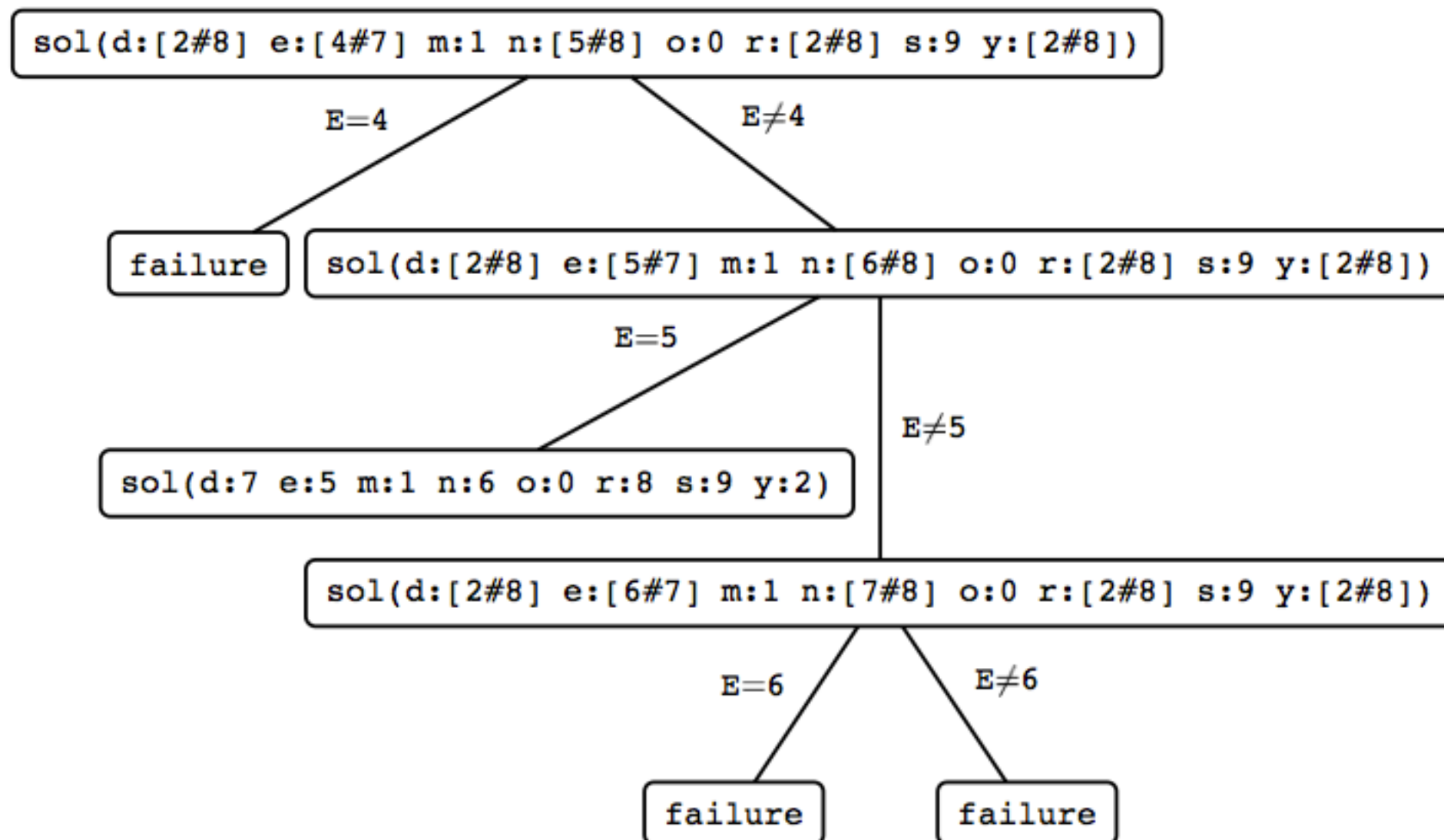
PETER VAN ROY and SEIF HARIDI



**Figure 3.1** A script for the Send More Money Puzzle.

```
proc {Money Root}
  S E N D M O R Y
in
  Root = sol(s:S e:E n:N d:D m:M o:O r:R y:Y)           % 1
  Root ::: 0#9                                           % 2
  {FD.distinct Root}                                     % 3
  S \=: 0                                                % 4
  M \=: 0
  1000*S + 100*E + 10*N + D                             % 5
+ 1000*M + 100*O + 10*R + E
=: 10000*M + 1000*O + 100*N + 10*E + Y
  {FD.distribute ff Root}
end
```

**Figure 3.2** The search tree explored by *Money*.

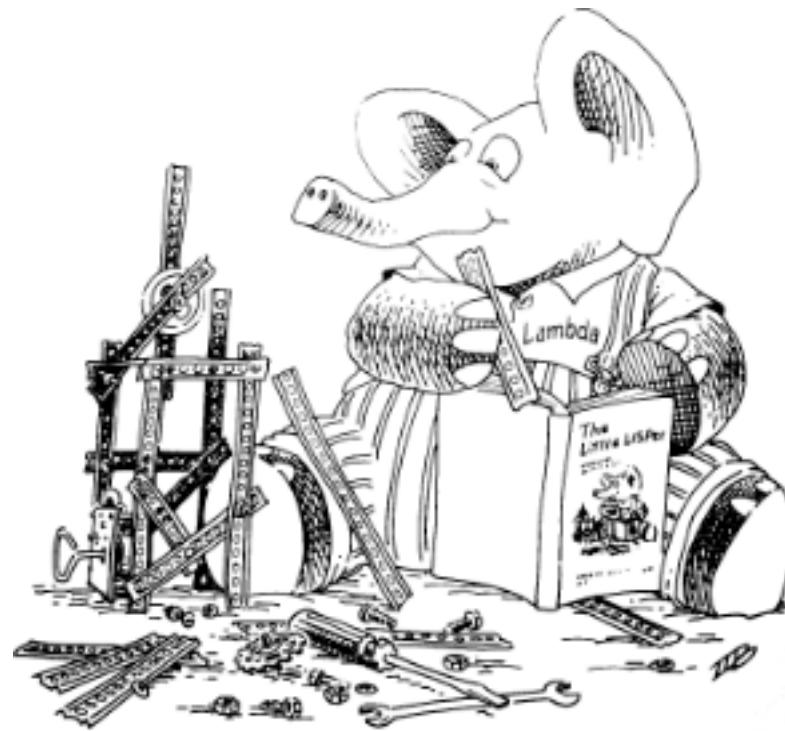




- cKanren only runs interval constraints once!

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- To avoid an infinite loop constraints are taken out of the store when run, and added back only when triggered constraints have completed





What if ...



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- Fixpoint, no constraint could change any domains

# Running

(fd/+ x y z)

# Queued

# Running

(fd/+ x y z)

# Queued

(fd/\* a b y)

(fd/+ c d y)



# Running

# Queued

(fd/\* a b y)

(fd/+ c d y)

# Running

(fd/\* a b y)

# Queued

(fd/+ c d y)

# Running

(fd/\* a b y)

# Queued

(fd/+ c d y)

(fd/+ x y z)

```
([clojure.core.logic.fd/* [100 <lvar:e6524> <lvar:G__59086535>]]
 [clojure.core.logic.fd/* [10 <lvar:e6524> <lvar:G__59246551>]]
 [clojure.core.logic.fd/+ [<lvar:G__59176544> <lvar:e6524> <lvar:G__59166543>]]
 [clojure.core.logic.fd/+ [<lvar:d6526> <lvar:G__59126539> <lvar:G__59116538>]]
 [clojure.core.logic.fd/* [100 <lvar:n6525> <lvar:G__59226549>]]
 [clojure.core.logic.fd/* [10 <lvar:n6525> <lvar:G__59106537>]]
 [clojure.core.logic.fd/* [1000 <lvar:s6523> <lvar:G__59066533>]]
 [clojure.core.logic.fd/* [1000 <lvar:o6528> <lvar:G__59206547>]]
 [clojure.core.logic.fd/* [100 <lvar:o6528> <lvar:G__59156542>]]
 [clojure.core.logic.fd/+ [<lvar:G__59246551> <lvar:y6530> <lvar:G__59236550>]]
 [clojure.core.logic.fd/* [10 <lvar:r6529> <lvar:G__59176544>]]
 [clojure.core.logic.fd/+ [<lvar:G__59136540> <lvar:G__59146541> <lvar:G__59126539>]]
 [clojure.core.logic.fd/* [10000 <lvar:m6527> <lvar:G__59186545>]])
```

578 calls to run-constraint

22 calls to map-sum

```

(defn cryptarithfd-1 []
  (run-nc* [s e n d m o r y :as q]
    (fd/in s e n d m o r y (fd/interval 0 9))
    (fd/distinct q)
    (fd/!= m 0) (fd/!= s 0)
    (fd/eq
      (=
        (+ (* 1000 s) (* 100 e) (* 10 n) d
          (* 1000 m) (* 100 o) (* 10 r) e)
        (+ (* 10000 m) (* 1000 o) (* 100 n) (* 10 e) y))))))

```

**Figure 3.1** A script for the Send More Money Puzzle.

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  S E N D M O R Y
in
  Root = sol(s:S e:E n:N d:D m:M o:O r:R y:Y)           % 1
  Root ::: 0#9                                           % 2
  {FD.distinct Root}                                     % 3
  S \=: 0                                                % 4
  M \=: 0
  1000*S + 100*E + 10*N + D                             % 5
+ 1000*M + 100*O + 10*R + E
=: 10000*M + 1000*O + 100*N + 10*E + Y
  {FD.distribute ff Root}
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```



~15ms on Clojure JVM



- ◉ core.logic SEND+MORE=MONEY still involves too much search

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- ◉ We don't have equation level constraints

- `core.logic SEND+MORE=MONEY` still involves too much search
- We don't have equation level constraints
- We should see precisely the amount of search as demonstrated by Mozart/OZ

# Anatomy of a Constraint



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- Like goals, constraints are just closures. They return a reified object that implements IFn and satisfies a number of custom protocols (subject to change)
- We can support much of the necessary “meta” behavior of cKanren constraints without macros
- yet leave the door open to use macros to provide a friendlier interface

```
(defn -domc [x]
  (reify
    IEnforceableConstraint
    clojure.lang.IFn
    (invoke [this s]
      (when (member? (get-dom s x) (walk s x))
        (rem-dom s x ::l/fd)))
    IConstraintOp
    (rator [_] `domc)
    (rands [_] [x])
    IRelevant
    (-relevant? [this s]
      (not (nil? (get-dom s x))))
    IRunnable
    (runnable? [this s]
      (not (lvar? (walk s x))))
    IConstraintWatchedStores
    (watched-stores [this] #{::l/subst})))
```

Invoke like a  
normal function



```
(defn -domc [x]
  (reify
    IEnforceableConstraint
    clojure.lang.IFn
    (invoke [this s]
      (when (member? (get-dom s x) (walk s x))
        (rem-dom s x ::1/fd)))
    IConstraintOp
    (rator [_] `domc)
    (rands [_] [x])
    IRelevant
    (-relevant? [this s]
      (not (nil? (get-dom s x))))
    IRunnable
    (runnable? [this s]
      (not (lvar? (walk s x))))
    IConstraintWatchedStores
    (watched-stores [this] #{::1/subst})))
```

What vars are  
associated with  
this constraint?



```
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  (reify
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    (invoke [this s]
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        (rem-dom s x ::1/fd)))
    IConstraintOp
    (rator [_] `domc)
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    IRelevant
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```

```

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  (reify
    IEnforceableConstraint
    clojure.lang.IFn
    (invoke [this s]
      (when (member? (get-dom s x) (walk s x))
        (rem-dom s x ::l/fd)))
    IConstraintOp
    (rator [_] `domc)
    (rands [_] [x])
    IRelevant
    (-relevant? [this s]
      (not (nil? (get-dom s x))))
    IRunnable
    (runnable? [this s]
      (not (lvar? (walk s x))))
    IConstraintWatchedStores
    (watched-stores [this] #{::l/subst})))

```



What var changes do we care about?

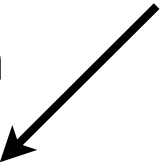
# First run

```
(defn cgoal [c]
  (reify
    clojure.lang.IFn
    (invoke [_ a]
      (if (runnable? c a)
        (when-let [a (c a)]
          (if (and (irelevant? c) (relevant? c a))
            ((addcg c) a)
            a))
          ((addcg c) a)))
    ...)))
```



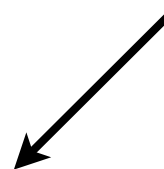
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              ((addcg c) a)
              a))
          ((addcg c) a)))
    ...)))
```

vroom vroom?



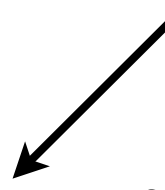
```
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  (reify
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    (invoke [_ a]
      (if (runnable? c a)
        (when-let [a (c a)]
          (if (and (irelevant? c) (relevant? c a))
              ((addcg c) a)
              a))
          ((addcg c) a)))
    ...)))
```

did it work?



```
(defn cgoal [c]
  (reify
    clojure.lang.IFn
    (invoke [_ a]
      (if (runnable? c a)
        (when-let [a (c a)]
          (if (and (irelevant? c) (relevant? c a))
            ((addcg c) a)
            a))
          ((addcg c) a)))
    ...)))
```

are we there yet?



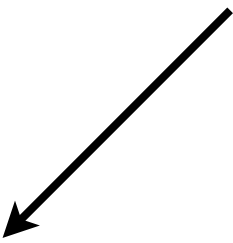
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  (reify
    clojure.lang.IFn
    (invoke [_ a]
      (if (runnable? c a)
        (when-let [a (c a)]
          (if (and (irelevant? c) (relevant? c a))
            ((addcg c) a)
            a)))
      ((addcg c) a)))
  ...))
```

Add to constraint store!



# Subsequent runs

```
(defn run-constraint [c]
  (fn [a]
    (if (or (not (irelevant? c)) (relevant? c a))
      (if (runnable? c a)
        ((composeg* (runcg c) c (stopcg c)) a)
        a)
      ((remcg c) a))))
```




```
(defn run-constraint [c]
  (fn [a]
    (if (or (not (irelevant? c)) (relevant? c a))
      (if (runnable? c a)
        ((composeg* (runcg c) c (stopcg c)) a)
        a)
      ((remcg c) a))))
```


```
(defn run-constraint [c]
  (fn [a]
    (if (or (not (irelevant? c)) (relevant? c a))
      → (if (runnable? c a)
          ((composeg* (runcg c) c (stopcg c)) a)
          a)
        ((remcg c) a))))
```



```
(defn run-constraint [c]
  (fn [a]
    (if (or (not (irelevant? c)) (relevant? c a))
      (if (runnable? c a)
          ((composeg* (runcg c) c (stopcg c)) a)
          a)
      ((remcg c) a))))
```



```
(defn run-constraint [c]
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# Complications

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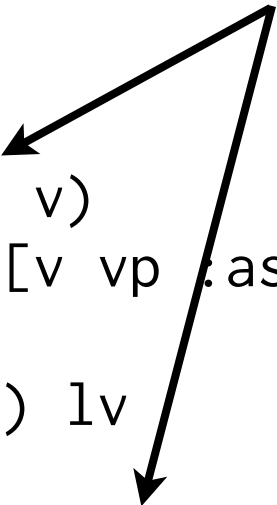
- LVars can point to normal Clojure values
- *Or* be unbound and point to domain information, SubstValue
- walk (lvar lookup) knows not to return SubstValue
- so need to use root-val for access to SubstValue

```
(walk [this v]
  (if (bindable? v)
    (loop [lv v [v vp :as me] (find s v)]
      (cond
        (nil? me) lv

        (not (bindable? vp))
        (if (subst-val? vp)
          (let [sv (:v vp)]
            (if (= sv ::unbound)
              (with-meta v (assoc (meta vp) ::unbound true))
              sv))
          vp)

        :else (recur vp (find s vp))))
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Note, not calls to lvar? :)



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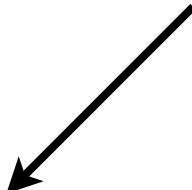
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- Unification may mean we need to re-root
  - and migrate constraints

$\{x \langle \text{interval } 1 \ 3 \rangle,$   
 $y \langle \text{interval } 2 \ 4 \rangle\}$

$\{x \text{ <interval 2 3>},$   
 $y \ x\}$

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- $\alpha$ Kanren is a first step, each new constraint domain, more confidence

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- ... what else?

# Thanks!

# Questions?