

# Redex: Practical Semantics Engineering

Version 6.0

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February 18, 2014

PLT Redex consists of a domain-specific language for specifying reduction semantics, plus a suite of tools for working with the semantics.

This manual consists of two parts: a tutorial introduction and a reference for Redex. Also see <http://redex.racket-lang.org/> and the `examples` subdirectory in the `redex` collection.

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# 1 Amb: A Redex Tutorial

This tutorial is designed for those familiar with the call-by-value  $\lambda$ -calculus (and evaluation contexts), but not Redex. The tutorial works though a model of the  $\lambda$ -calculus extended with a variation on McCarthy's `amb` operator for ambiguous choice (McCarthy 1963; Zabih et al. 1987).

If you are not familiar with Racket, first try *Quick: An Introduction to Racket with Pictures or More: Systems Programming with Racket*.

The model includes a standard evaluation reduction relation and a type system. Along the way, the tutorial demonstrates Redex's support for unit testing, random testing, typesetting, metafunctions, reduction relations, and judgment forms. It also includes a number of exercises to use as jumping off points to explore Redex in more depth, and each of the functions and syntactic forms used in the examples are linked to more information.

## 1.1 Defining a Language

To get started, open DrRacket, and put the following two lines at the top of the file (if the first line is not there already, use the Language|Choose Language... menu item to make sure that DrRacket is set to use the language declaration in the source).

```
#lang racket
(require redex)
```

Those lines tell DrRacket that we're writing a program in the `racket` language and we're going to be using the `redex` DSL.

Next, enter the following definition.

```
(define-language L
  (e (e e)
     ( $\lambda$  (x t) e)
     x
     (amb e ...)
     number
     (+ e ...)
     (if0 e e e)
     (fix e))
  (t ( $\rightarrow$  t t) num)
  (x variable-not-otherwise-mentioned))
```

The `define-language` form gives a name to a grammar. In this case, `L` is the Racket-level name referring to the grammar containing the non-terminal `e`, with six productions

(application, abstraction, variables, `amb` expressions, numbers, and addition expressions), the non-terminal `t` with two productions, and the non-terminal `x` that uses the pattern keyword `variable-not-otherwise-mentioned`. This special pattern matches all symbols except those used as literals in the grammar (in this case: `λ`, `amb`, `+`, and `→`).

Once we have defined the grammar, we can ask Redex if specific terms match the grammar. This expression checks to see if the `e` non-terminal (from `L`) matches the object-language expression `(λ (x) x)`.

To do this, first click the Run button in DrRacket's toolbar and then enter the following expression after the prompt. For the remainder of this tutorial, expressions prefixed with a `>` are intended to be run in the interactions window (lower pane), and expressions without the `>` prefix belong in the definitions window (the upper pane).

```
> (redex-match
  L
  e
  (term (λ (x) x)))
#f
```

In general, a `redex-match` expression first names a language, then a pattern, and then its third position is an arbitrary Racket expression. In this case, we use `term` to construct an Redex object-level expression. The `term` operator is much like Lisp's `quasiquote` (typically written `'`).

This term does not match `e` (since `e` insists the function parameters come with types), so Redex responds with `#f`, false.

When an expression does match, as with this one:

```
> (redex-match
  L
  e
  (term ((λ (x num) (amb x 1))
        (+ 1 2))))
(list
 (match
  (list
   (bind
    'e
    '((λ (x num) (amb x 1)) (+ 1 2))))))
```

Redex responds with bindings for all of the pattern variables. In this case, there is just one, `e`, and it matches the entire expression.

We can also use matching to extract sub-pieces. For example, we can pull out the function and argument position of an application expression like this:

```

> (redex-match
  L
  (e_1 e_2)
  (term ((λ (x num) (amb x 1))
        (+ 1 2))))
(list
 (match
  (list
   (bind 'e_1 '(λ (x num) (amb x 1)))
   (bind 'e_2 '(+ 1 2))))))

```

As you probably noticed, `redex-match` returns a list of matches, not just a single match. The previous matches each only matched a single way, so the corresponding lists only have a single element. But a pattern may be ambiguous, e.g., the following pattern which matches any non-empty sequence of expressions, but binds different elements of the sequence in different ways:

```

> (redex-match
  L
  (e_1 ... e_2 e_3 ...)
  (term ((+ 1 2)
        (+ 3 4)
        (+ 5 6))))
(list
 (match
  (list
   (bind 'e_1 '())
   (bind 'e_2 '(+ 1 2))
   (bind 'e_3 '((+ 3 4) (+ 5 6))))))
 (match
  (list
   (bind 'e_1 '((+ 1 2)))
   (bind 'e_2 '(+ 3 4))
   (bind 'e_3 '((+ 5 6))))))
 (match
  (list
   (bind 'e_1 '((+ 1 2) (+ 3 4)))
   (bind 'e_2 '(+ 5 6))
   (bind 'e_3 '()))))

```

### Exercise 1

Use `redex-match` to extract the body of the function from this object-language program:

```
((λ (x) (+ x 1)))
```

17)

## Exercise 2

Use `redex-match` to extract the range portion of the type `(→ num (→ num num))`.

## Exercise 3

Redex's pattern language supports ambiguity through non-terminals, the `in-hole` pattern, and ellipsis placement (as in the example just above). Use the latter source of ambiguity to design a pattern that matches one way for each adjacent pair of expressions in a sequence. That is, if you match the sequence `(1 2 3 4)`, then you'd expect one match for 1 & 2, one match for 2 & 3, and one match for 3 & 4. In general, this pattern should produce  $n$  matches when there are  $n+1$  expressions in the sequence.

To test your solution use `redex-match` like this:

```
(redex-match
  L
  ; your solution goes here
  (term (1 2 3 4)))
```

where you expect a result like this

```
(list
  (match (list (bind 'e_1 1) (bind 'e_2 2)))
  (match (list (bind 'e_1 2) (bind 'e_2 3)))
  (match (list (bind 'e_1 3) (bind 'e_2 4))))
```

but possibly with more pattern variables in the resulting match.

## Exercise 4

The ellipsis pattern can also be “named” via subscripts that, when duplicated, force the lengths of the corresponding sequences to match. For example, the pattern

```
((λ (x ...) e) v ...)
```

matches application expressions where the function may have a different arity than the number of arguments it receives, but the pattern:

```
((λ (x ..._1) e) v ..._1)
```

ensures that the number of `xs` is the same as the number of `vs`.

Use this facility to write a pattern that matches odd length lists of expressions, returning one match for each pair of expressions that are equidistant from the ends of the sequence. For example, if matching the sequence `(1 2 3 4 5)`, there would be two matches, one for the pair `1 & 5` and another for the pair `2 & 4`. Your match should include the the bindings `e_left` and `e_right` that extract these pairs (one element of the pair bound to `e_left` and the other to `e_right`). Test your pattern with `redex-match`.

## 1.2 Typing

To support a type system for our language, we need to define type environments, which we do by extending the language `L` with a new non-terminal `Γ`, that we use to represent environments.

```
(define-extended-language L+Γ L
  [Γ · (x : t Γ)])
```

The `define-extended-language` form accepts the name of the new language, the name of the extended language and then a series of non-terminals just like `define-language`.

In the extended language, we can give all of the typing rules for our language. Ignoring the `#:mode` specification for a moment, the beginning of this use of `define-judgment-form` has a contract declaration indicating that the judgments all have the shape `(types Γ e t)`.

```
(define-judgment-form
  L+Γ
  #:mode (types I I 0)
  #:contract (types Γ e t)

  [(types Γ e_1 (→ t_2 t_3))
   (types Γ e_2 t_2)
   -----
   (types Γ (e_1 e_2) t_3)]

  [(types (x : t_1 Γ) e t_2)
   -----
   (types Γ (λ (x t_1) e) (→ t_1 t_2))]

  [(types Γ e (→ (→ t_1 t_2) (→ t_1 t_2)))
   -----
   (types Γ (fix e) (→ t_1 t_2))]

  [-----]
```

```

(types (x : t Γ) x t)]

[(types Γ x_1 t_1)
 (side-condition (different x_1 x_2))
 -----]
(types (x_2 : t_2 Γ) x_1 t_1)]

[(types Γ e num) ...
 -----]
(types Γ (+ e ...) num)]

[-----]
(types Γ number num)]

[(types Γ e_1 num)
 (types Γ e_2 t)
 (types Γ e_3 t)
 -----]
(types Γ (if0 e_1 e_2 e_3) t)]

[(types Γ e num) ...
 -----]
(types Γ (amb e ...) num)]

```

The first clause gives the typing rule for application expressions, saying that if `e_1` has the type  $(\rightarrow t_2 t_3)$  and `e_2` has the type `t_2`, then the application expression has the type `t_3`.

Similarly, the other clauses give the typing rules for all of the other forms in the language.

Most of the rules use `types`, or give base types to atomic expressions, but the fourth rule is worth a special look. It says that if a variable typechecks in some environment, then it also type checks in an extended environment, provided that the environment extension does not use the variable in question.

The `different` function is a metafunction, defined as you might expect:

```

(define-metafunction L+Γ
  [(different x_1 x_1) #f]
  [(different x_1 x_2) #t])

```

The `#:mode` specification tells Redex how to compute derivations. In this case, the mode specification indicates that `Γ` and `e` are to be thought of as inputs, and the type position is to be thought of as an output.



Redex then checks that spec, making sure that, given a particular  $\Gamma$  and  $e$ , it can compute a  $t$  or, perhaps, multiple  $t$ s (if the patterns are ambiguous, or if multiple rules apply to a given pair of  $\Gamma$  and  $e$ ).

### 1.3 Testing Typing

The `judgment-holds` form checks to see if a potential judgment is derivable. For example,

```
> (judgment-holds
  (types .
    ((λ (x num) (amb x 1))
     (+ 1 2))
    t)
  '(num))
```

computes all of the types that the expression

```
((λ (x num) (amb x 1))
 (+ 1 2))
```

has, returning a list of them (in this case, just one).

In general, the `judgment-holds` form's first argument is an instance of some judgment-form that should have concrete terms for the  $I$  positions in the mode spec, and patterns in the positions labelled  $O$ . Then, the second position in `judgment-holds` is an expression that can use the pattern variables inside those  $O$  positions. The result of `judgment-holds` will be a list of terms, one for each way that the pattern variables in the  $O$  positions can be filled when evaluating `judgment-holds`'s second position.

For example, if we wanted to extract only the range position of the type of some function, we could write this:

```
> (judgment-holds
  (types .
    (λ (f (→ num (→ num num))) (f (amb 1 2)))
    (→ t_1 t_2))
  t_2)
  '((→ num num))
```

The result of this expression is a singleton list containing the function type that maps numbers to numbers. The reason you see two open parentheses is that Redex exploits Racket's s-expressions to reflect Redex terms as Racket values. Here's another way to write the same value

```
> (list (term (→ num num)))
'((→ num num))
```

Racket's printer does not know that it should use `term` for the inner lists and `list` (or `quote`) for the outer list, so it just uses the quote notation for all of them.

We can combine `judgment-holds` with Redex's unit test support to build a small test suite:

```
> (test-equal
  (judgment-holds
   (types · (λ (x num) x) t)
   t)
  (list (term (→ num num))))
```

```
> (test-equal
  (judgment-holds
   (types · (amb 1 2 3) t)
   t)
  (list (term num)))
```

```
> (test-equal
  (judgment-holds
   (types · (+ 1 2) t)
   t)
  (list (term (→ num num))))
```

```
FAILED :27.0
actual: '(num)
expected: '((→ num num))
```

Redex is silent when tests pass and gives the source location for the failures, as above. The `test-equal` form accepts two expressions, evaluates them, and checks to see if they are `equal?` (structural equality).

To see a summary of the tests run so far, call `test-results`.

```
> (test-results)
1 test failed (out of 3 total).
```

## Exercise 5

Remove the `different` side-condition and demonstrate how one expression now has multiple types, using `judgment-holds`. That is, find a use of `judgment-holds` that returns a list of length two, with two different types in it.

## Exercise 6

The typing rule for `amb` is overly restrictive. In general, it would be better to have a rule like this one:

$$\frac{[(\text{types } \Gamma \ e \ t) \ \dots]}{(\text{types } \Gamma \ (\text{amb } e \ \dots) \ t)}$$

but Redex does not support this rule because the mode specification is not satisfied in the case that `amb` has no subexpressions. That is, any type should be okay in this case, but Redex cannot “guess” which type is the one needed for a particular derivation, so it rejects the entire `define-judgment-form` definition. (The error message is different, but this is the ultimate cause of the problem.)

Fix this by annotating `amb` expressions with their types, making suitable changes to the language as well as the `define-judgment-form` for `types`. Add new test cases to make sure you’ve done this properly.

## 1.4 Defining a Reduction Relation

To reduce terms, Redex provides `reduction-relation`, a form that defines unary relations by cases. To define a reduction relation for our `amb` language, we first need to define the evaluation contexts and values, so we extend the language a second time.

```
(define-extended-language Ev L+Γ
  (p (e ...))
  (P (e ... E e ...))
  (E (v E)
     (E e)
     (+ v ... E e ...))
  (if0 E e e)
  (fix E)
  hole)
(v (λ (x t) e)
   (fix v)
   number))
```

To give a suitable notion of evaluation for `amb`, we define `p`, a non-terminal for programs. Each program consists of a sequence of expressions and we will use them to represent the possible ways in which an `amb` expression could have been evaluated. Initially, we will simply wrap an expression in a pair of parentheses to generate a program that consists of that single expression.

The non-terminal `P` gives the corresponding evaluation contexts for `ps` and says that evaluation can occur in any of them, without restriction. The grammar for `E` dictates that reduction may occur inside application expressions and addition expressions, always from left to right.

To prepare for the reduction relation, we first define a metafunction for summation.

```
(define-metafunction Ev
  Σ : number ... -> number
  [(Σ number ...)
   ,(apply + (term (number ...)))])
```

This lifts the Racket function `+` to Redex, giving it the name `Σ`. The unquote (comma) in the definition of the metafunction escapes into Racket, using `apply` and `+` to sum up the sequence of numbers that were passed to `Σ`. As we've noted before, the `term` operator is like Racket's `quasiquote` operator, but it is also sensitive to Redex pattern variables. In this case, `(term (number ...))` produces a list of numbers, extracting the arguments from the call to `Σ`.

To define a reduction relation, we also have to define substitution. Generally speaking, substitution functions are tricky to get right and, since they generally are not shown in papers, we have defined a workhorse substitution function in Racket that runs in near linear time. The source code is included with Redex. If you'd like to have a look, evaluate the expression below in the REPL to find the precise path on your system:

```
(collection-file-path "tut-subst.rkt" "redex")
```

(Test cases are in `"test/tut-subst-test.rkt"`, relative to `"tut-subst.rkt"`.)

That file contains the definition of the function `subst/proc`, which expects four arguments: a predicate for determining if an expression is a variable, a list of variables to replace, a list of terms to replace them with, and a term to do the replacement inside (the function has a hard-wired notion of the shape of all binding forms, but is agnostic to the other expression forms in the language).

To use this substitution function, we also need to lift it into Redex, just like we did for `Σ`.

```
(require redex/tut-subst)
(define-metafunction Ev
  subst : x v e -> e
  [(subst x v e)
   ,(subst/proc x? (list (term x)) (list (term v)) (term e))])
(define x? (redex-match Ev x))
```

In this case, we use `term` to extract the values of the Redex variables `x`, `v`, and `e` and then pass them to `subst/proc`.

The definition of `x?` uses a specialized, more efficient form of `redex-match`; supplying `redex-match` with only two arguments permits Redex to do some processing of the pattern, and it results in a predicate that matches the pattern in the given language (which we can supply directly to `subst/proc`).

Using that substitution function, we can now give the reduction relation.

```
(define red
  (reduction-relation
    Ev
    #:domain p
    (--> (in-hole P (if0 0 e_1 e_2))
         (in-hole P e_1)
         "if0t")
    (--> (in-hole P (if0 v e_1 e_2))
         (in-hole P e_2)
         (side-condition (not (equal? 0 (term v))))
         "if0f")
    (--> (in-hole P ((fix (λ (x t) e)) v))
         (in-hole P (((λ (x t) e) (fix (λ (x t) e))) v))
         "fix")
    (--> (in-hole P ((λ (x t) e) v))
         (in-hole P (subst x v e))
         "βv")
    (--> (in-hole P (+ number ...))
         (in-hole P (Σ number ...))
         "+")
    (--> (e_1 ... (in-hole E (amb e_2 ...)) e_3 ...)
         (e_1 ... (in-hole E e_2) ... e_3 ...)
         "amb")))
```

The `reduction-relation` form accepts the name of a language, the domain of the relation (`p` in this case), and then a series of rewriting rules, each of the form `(--> pattern pattern)`.

The first rule replaces `if0` expressions when the test position is `0` by the second subexpression (the true branch). It uses the `in-hole` pattern, the Redex notation for context decomposition. In this case, it decomposes a program into some `P` with an appropriate `if0` expression inside, and then the right-hand side of the rule places `e_1` into the same context.

The rule for the false branch should apply when the test position is any value except `0`. To establish this, we use a `side-condition`. In general, a side-condition is a Racket expression that is evaluated for expressions where the pattern matches; if it returns true, then the rule fires. In this case, we use `term` to extract the value of `v` and then compare it with `0`.

To explore the behavior of a reduction relation, Redex provides `traces` and `stepper`. They both accept a reduction relation and a term, and then show you how that term reduces in a

GUI. The GUI that `traces` uses is better suited to a quick overview of the reduction graph and `stepper` is better for more detailed explorations of reduction graphs that have larger expressions in them.

### Exercise 7

Evaluate

```
(traces red
  (term ((+ (amb 1 2)
            (amb 10 20)))))
```

It does not show all of the terms by default, but one click the Reduce button shows them all.

If you have Graphviz installed, Redex can use it to lay out the graph; click Fix Layout and Redex will call out to dot to lay out the graph.

### Exercise 8

Design a function that accepts a number `n` and evaluates (ambiguously) to any of the numbers between `n` and 0. Call it with 10 and look at the results in both `traces` and `stepper`.

Hint: to subtract 1 from `n`, use `(+ n -1)`

## 1.5 Testing Reduction Relations

Redex provides `test-->` for using testing the transitive closure of a reduction relation. If you supply it a reduction relation and two terms, it will reduce the first term and make sure that it yields the second.

```
> (test-->
  red
  (term ((if0 1 2 3)))
  (term (3)))

> (test-->
  red
  (term ((+ (amb 1 2)
            (amb 10 20)))))
  (term (11 21 12 22)))

> (test-results)
Both tests passed.
```

The `test-->` form is like `test-->>`, except that it only reduces the term a single step.

```
> (test-->
  red
  (term ((+ (amb 1 2) 3)))
  (term ((+ 1 3) (+ 2 3))))

> (test-results)
One test passed.
```

If a term produces multiple results, then each of the results must be listed.

```
> (test-->
  red
  (term ((+ 1 2) (+ 3 4)))
  (term (3 (+ 3 4)))
  (term ((+ 1 2) 7)))

> (test-results)
One test passed.
```

Technically, when using `test-->>`, it finds all irreducible terms that are reachable from the given term, and expects them all to be listed, with one special case: when it detects a cycle in the reduction graph, then it signals an error. (Watch out: when the reduction graph is infinite and there are no cycles, then `test-->>` consumes all available memory.)

```
> (test-->>
  red
  (term (((fix (λ (x) (→ num num)) x)) 1))))
FAILED :46.0
found a cycle in the reduction graph

> (test-results)
1 test failed (out of 1 total).
```

To suppress this behavior, pass `#:cycles-ok` to `test-->>`.

```
> (test-->>
  red #:cycles-ok
  (term (((fix (λ (x) (→ num num)) x)) 1))))

> (test-results)
One test passed.
```

This test case has no expected results but still passes, since there are no irreducible terms reachable from the given term.

### Exercise 9

Extend  $\lambda$  to support multiple arguments. Use the notation  $(\lambda (x \ t) \dots e)$  for multi-arity  $\lambda$  expressions because the `subst/proc` function works properly with  $\lambda$  expressions of that shape. Use this definition of `subst`.

```
(define-metafunction Ev
  subst : (x v) ... e -> e
  [(subst (x v) ... e)
   ,(subst/proc x?
                (term (x ...))
                (term (v ...))
                (term e))])
```

Also, adjust the typing rules (and do not forget that an ellipsis can be named, as discussed in exercise 4).

## 1.6 Random Testing

Random testing is a cheap and easy way to find counter-examples to false claims. Unsurprisingly, it is hard to pin down exactly which false claims that random testing can provide counter-examples to. Hanford (1970) put it best (calling his random test case generator a syntax machine): “[a]lthough as a writer of test cases, the syntax machine is certainly unintelligent, it is also uninhibited. It can test a [language] processor with many combinations that would not be thought of by a human test case writer.”

To get a sense of how random testing works, we define this Racket predicate

```
(define (progress-holds? e)
  (if (types? e)
      (or (v? e)
          (reduces? e))
      #t))
```

that captures the statement of the progress result.

The three helper functions `types?`, `v?`, and `reduces?` can be defined by using our earlier definitions of typing, the grammar, and the reduction relation, plus calls into `Redex`:



```

(define (types? e)
  (not (null? (judgment-holds (types . ,e t)
                              t))))

(define v? (redex-match Ev v))

(define (reduces? e)
  (not (null? (apply-reduction-relation
              red
              (term (,e))))))

```

The only new construct here is `apply-reduction-relation`, which accepts a reduction and a term, and returns a list of expressions that it reduces to in a single step. Thus, `reduces?` returns `#t` when the given term is reducible and `#f` otherwise.

Putting all of that together with `redex-check` will cause Redex to randomly generate 1,000 es and attempt to falsify them:

```

> (redex-check Ev e (progress-holds? (term e)))
redex-check: no counterexamples in 1000 attempts

```

The `redex-check` form accepts the name of a language (`Ev` in this case), a pattern (`e` in this case), and a Racket expression that returns a boolean. It randomly generates expressions matching the pattern and then invokes the expression in an attempt to elicit `#f` from the Racket expression.

We can also ask `redex-check` how good of a job it is doing. Specifically, this expression re-runs the same random test, but this time sets up some instrumenting infrastructure to determine how many of the reduction rules fire during the testing. In this case, we create a coverage value that indicates that we're interested in how many of the rules in `red` fired, and then we install it using the `relation-coverage` parameter. In the dynamic extent of the `parameterize`, then, the relation will record how it gets tested. Once that returns we can use `covered-cases` to see exactly how many times each case fired.

```

> (let ([c (make-coverage red)])
  (parameterize ([relation-coverage (list c)])
    (redex-check Ev e (progress-holds? (term e))))
  (covered-cases c))
redex-check: no counterexamples in 1000 attempts
'(("+" . 70)
  ("amb" . 49)
  ("fix" . 0)
  ("if0f" . 1)
  ("if0t" . 1)
  ("βv" . 0))

```

Not many of them! To improve coverage, we can tell `redex-check` to try generating expressions using the patterns on the left-hand side of the rules to generate programs, and then check to see if progress for each of the expressions in the program:

```
> (check-reduction-relation
    red
    (λ (p) (andmap progress-holds? p)))
check-reduction-relation: no counterexamples in 1000 attempts
(with each clause)
```

The `check-reduction-relation` is a shorthand for using `redex-check` to generate elements of the domain of the given reduction relation (`red` in this case), and then pass them to the given function, attempting to elicit `#f`.

In this case, since the domain of `red` is `p`, the random generator produces sequences of `e` expressions, which are reflected into `Redex` as lists, and so we simply try to see if progress holds for each element of the list, using `andmap`.

Still no test failures, but installing the same coverage testing boilerplate around the call to `check-reduction-relation` tells us that we got much better coverage of the reduction system.

```
> (let ([c (make-coverage red)])
    (parameterize ([relation-coverage (list c)])
      (check-reduction-relation
        red
        (λ (p) (andmap progress-holds? p)))
      (covered-cases c)))
check-reduction-relation: no counterexamples in 1000 attempts
(with each clause)
'(("+" . 2050)
  ("amb" . 2108)
  ("fix" . 2)
  ("if0f" . 246)
  ("if0t" . 106)
  ("βv" . 53))
```

### Exercise 10

Remove one of the productions from `E` (except `hole`) and find an expression in the revised system that causes `progress?` to return `#f`.

See if `redex-check` can also falsify progress for the same system.

### Exercise 11

Formulate and randomly check type preservation. Usually, this lemma says that if an expression has a type and it takes a step, then it produces an expression with the same type. In this case, however, formulate a predicate that accepts an expression and checks that, if it has a type and takes a step, then all of the resulting expressions in the new program have the same type.

## 1.7 Typesetting the Reduction Relation

Redex's typesetting facilities accept languages, metafunctions, reduction relations, and judgment-forms and produce typeset output that can be included directly into a figure in a paper.

```
> (render-reduction-relation red)
P[(if0 0 e1 e2)] → [if0t]
P[e1]
P[(if0 v e1 e2)] → [if0f]
P[e2]
      where (not (equal? 0 v))
P[((fix (λ (x t) e)) v)] → [fix]
P[((λ (x t) e) (fix (λ (x t) e))) v]
P[((λ (x t) e) v)] → [βv]
P[subst[[x, v, e]]]
P[(+ number ...)] → [+]
P[Σ[[number, ...]]]
(e1 ... E[(amb e2 ...)] e3 ...) → [amb]
(e1 ... E[e2] ... e3 ...)
```

The result of `render-reduction-relation` is rendered directly in DrRacket's interactions window, and also can be saved as a ".ps" file by passing the name of the file as the second argument to `render-reduction-relation`.

Redex's typesetting also interoperates with the `pict` library. If we pull it in with a `require`:

```
(require pict)
```

then we can use the `pict` primitives to combine typeset fragments into a larger whole.

```
> (scale (vl-append
```

```
20
(language->pict Ev)
(reduction-relation->pict red))
3/2)
```

$$\begin{aligned}
p &::= (e \dots) \\
P &::= (e \dots E e \dots) \\
E &::= (v E) \\
&\quad | (E e) \\
&\quad | (+ v \dots E e \dots) \\
&\quad | (\text{if0 } E e e) \\
&\quad | (\text{fix } E) \\
&\quad | [] \\
v &::= (\lambda (x t) e) \\
&\quad | (\text{fix } v) \\
&\quad | \textit{number}
\end{aligned}$$

$$\begin{array}{l}
P[(\text{if0 } 0 e_1 e_2)] \longrightarrow \text{[if0t]} \\
P[e_1]
\end{array}$$

$$\begin{array}{l}
P[(\text{if0 } v e_1 e_2)] \longrightarrow \text{[if0f]} \\
P[e_2]
\end{array}$$

where  $(\text{not } (\text{equal? } 0 v))$

$$\begin{array}{l}
P[((\text{fix } (\lambda (x t) e)) v)] \longrightarrow \text{[fix]} \\
P[((\lambda (x t) e) (\text{fix } (\lambda (x t) e))) v]
\end{array}$$

$$\begin{array}{l}
P[((\lambda (x t) e) v)] \longrightarrow \text{[}\beta\text{v]} \\
P[\text{subst}[[x, v, e]]]
\end{array}$$

$$\begin{array}{l}
P[(+ \textit{number} \dots)] \longrightarrow \text{[+]} \\
P[\Sigma[[\textit{number}, \dots]]]
\end{array}$$

$$\begin{array}{l}
(e_1 \dots E[(\text{amb } e_2 \dots)] e_3 \dots) \longrightarrow \text{[amb]} \\
(e_1 \dots E[e_2] \dots e_3 \dots)_{21}
\end{array}$$

Generally speaking, Redex has reasonable default ways to typeset its definitions, except when they escapes to Racket. In that case, it typesets the code in a fixed-width font and makes the background pink to call our attention to it. While it is possible to use `with-unquote-rewriter` to tell Redex how to typeset those regions, often it is easier to define a metafunction and call it. In this case, we can use `different` (defined earlier).

```
(define if0-false-rule
  (reduction-relation
    Ev #:domain p
    (--> (in-hole P (if0 v e_1 e_2))
         (in-hole P e_2)
         (side-condition (term (different v 0)))
         "if0f")))
```

Now when we typeset this reduction-relation there is no pink.

```
> (render-reduction-relation if0-false-rule)
P[(if0 v e1 e2)]  $\longrightarrow$  [if0f]
P[e2]
  where different[[v, 0]]
```

Still, the typesetting is non-optimal, so we can use `with-compound-rewriter` to adjust the way calls to `different` typeset.

```
> (with-compound-rewriter
  'different
  (λ (lws)
    (list "" (list-ref lws 2) " ≠ " (list-ref lws 3) ""))
  (render-reduction-relation if0-false-rule))
P[(if0 v e1 e2)]  $\longrightarrow$  [if0f]
P[e2]
  where v ≠ 0
```

The compound rewriter is given a list of `lw` structs that correspond to the untypeset sequence for a use of `different`, and then can replace them with a different set of strings and `lws`. For more details on the structure of `lw` structs and to experiment with them, see `to-lw`.

## Exercise 12

Redex uses the indentation and newlines in the program source code to determine where the line breaks in the printed output goes, instead of using a pretty-printer, so as to give Redex programmers fine-grained control over how their models typeset.

Exploit this facility so that this expression produces an expression with a minimum amount of whitespace within its bounding box. (The call to `frame` helps to clarify where the bounding box is.)

```
(frame
  (vl-append
    20
    (language->pict Ev)
    (reduction-relation->pict red)))
```

That is, adjust the whitespace in `Ev` so that it fills as much of the width established by rendering `red`.

### Exercise 13

Typeset `types`. Use a compound rewriter so a use of `(type  $\Gamma$  e t)` is rendered as

$\Gamma \vdash e : t$

## Bibliography

- Kenneth V. Hanford. Automatic generation of test cases. *IBM Systems Journal* 9(4), pp. 244–257, 1970.
- John McCarthy. A Basis for a Mathematical Theory of Computation. In *Computer Programming And Formal Systems* by P. Braffort and D. Hirschberg (Ed.), 1963.
- Ramin Zabih, David McAllester, and David Chapman. Non-deterministic Lisp with dependency-directed backtracking. In *Proc. Proceedings of the Sixth National Conference on Artificial Intelligence*, pp. 59–64, 1987.

## 2 The Redex Reference

To load Redex use:

```
(require redex)      package: redex-gui-lib
```

which provides all of the names documented in this library.

Alternatively, use the `redex/reduction-semantic`s and `redex/pict` modules, which provide only non-GUI functionality (i.e., everything except `redex/gui`), making them suitable for programs which should not depend on `racket/gui/base`.

### 2.1 Patterns

```
(require redex/reduction-semantic)  package: redex-lib
```

This section covers Redex's *pattern* language, used in many of Redex's forms.

Note that pattern matching is caching (including caching the results of side-conditions). This means that once a pattern has matched a given term, Redex assumes that it will always match that term.

This is the grammar for the Redex pattern language. Non-terminal references are wrapped with angle brackets; otherwise identifiers in the grammar are terminals.

```
pattern = any
| -
| number
| natural
| integer
| real
| string
| boolean
| variable
| (variable-except <id> ...)
| (variable-prefix <id>)
| variable-not-otherwise-mentioned
| hole
| symbol
| (name <id> <pattern>)
| (in-hole <pattern> <pattern>)
| (hide-hole <pattern>)
| (side-condition <pattern> guard)
| (cross <id>)
| (<pattern-sequence> ...)
```



```

| <racket-constant>

pattern-sequence = <pattern>
| ... ; literal ellipsis
| ..._id

```

- The `_` pattern matches any sexpression. This pattern may also be suffixed with an underscore and another identifier, in which case they bind the full name (as if it were an implicit name pattern) and match the portion before the underscore.
- The `_` pattern matches any sexpression, but does not bind `$pattech[_]` as a name, nor can it be suffixed to bind a name.
- The `number` pattern matches any number. This pattern may also be suffixed with an underscore and another identifier, in which case they bind the full name (as if it were an implicit name pattern) and match the portion before the underscore.
- The `natural` pattern matches any exact non-negative integer. This pattern may also be suffixed with an underscore and another identifier, in which case they bind the full name (as if it were an implicit name pattern) and match the portion before the underscore.
- The `integer` pattern matches any exact integer. This pattern may also be suffixed with an underscore and another identifier, in which case they bind the full name (as if it were an implicit name pattern) and match the portion before the underscore.
- The `real` pattern matches any real number. This pattern may also be suffixed with an underscore and another identifier, in which case they bind the full name (as if it were an implicit name pattern) and match the portion before the underscore.
- The `string` pattern matches any string. This pattern may also be suffixed with an underscore and another identifier, in which case they bind the full name (as if it were an implicit name pattern) and match the portion before the underscore.
- The `boolean` pattern matches `#true` and `#false` (which are the same as `#t` and `#f`, respectively). This pattern may also be suffixed with an underscore and another identifier, in which case they bind the full name (as if it were an implicit name pattern) and match the portion before the underscore.
- The `variable` pattern matches any symbol. This pattern may also be suffixed with an underscore and another identifier, in which case they bind the full name (as if it were an implicit name pattern) and match the portion before the underscore.
- The `variable-except` pattern matches any symbol except those listed in its argument. This is useful for ensuring that keywords in the language are not accidentally captured by variables.
- The `variable-prefix` pattern matches any symbol that begins with the given prefix.

- The `variable-not-otherwise-mentioned` pattern matches any symbol except those that are used as literals elsewhere in the language.
- The `hole` pattern matches anything when inside the first argument to an in-hole pattern. Otherwise, it matches only a hole.
- The `symbol` pattern stands for a literal symbol that must match exactly, unless it is the name of a non-terminal in a relevant language or contains an underscore.

If it is a non-terminal, it matches any of the right-hand sides of that non-terminal. If the non-terminal appears twice in a single pattern, then the match is constrained to expressions that are the same, unless the pattern is part of a grammar, in which case there is no constraint.

If the symbol is a non-terminal followed by an underscore, for example `e_1`, it is implicitly the same as a name pattern that matches only the non-terminal, (`name e_1 e`) for the example. Accordingly, repeated uses of the same name are constrained to match the same expression.

If the symbol is a non-terminal followed by `!_`, for example `e !_1`, it is also treated as a pattern, but repeated uses of the same pattern are constrained to be different. For example, this pattern:

```
(e !_1 e !_1 e !_1)
```

matches lists of three `es`, but where all three of them are distinct.

Unlike a `_` pattern, the `!_` patterns do not bind names.

If `_` names and `!_` are mixed, they are treated as separate. That is, this pattern (`e_1 e !_1`) matches just the same things as (`e e`), but the second doesn't bind any variables.

If the symbol otherwise has an underscore, it is an error.

- The pattern (`name symbol pattern`) matches `pattern` and binds using it to the name `symbol`.
- The (`in-hole pattern pattern`) pattern matches the first `pattern`. This match must include exactly one match against the second `pattern`. If there are zero matches or more than one match, an exception is raised.  
When matching the first argument of in-hole, the `hole` pattern matches any `sexpression`. Then, the `sexpression` that matched the hole pattern is used to match against the second pattern.
- The (`hide-hole pattern`) pattern matches what the embedded `pattern` matches but if the pattern matcher is looking for a decomposition, it ignores any holes found in that `pattern`.
- The (`side-condition pattern guard`) pattern matches what the embedded `pattern` matches, and then the guard expression is evaluated. If it returns `#f`, the

pattern fails to match, and if it returns anything else, the pattern matches. Any occurrences of `name` in the pattern (including those implicitly there via `_ patterns`) are bound using `term-let` in the guard.

- The `(cross symbol)` pattern is used for the compatible closure functions. If the language contains a non-terminal with the same name as `symbol`, the pattern `(cross symbol)` matches the context that corresponds to the compatible closure of that non-terminal.
- The `(pattern-sequence ...)` pattern matches a sexpression list, where each pattern-sequence element matches an element of the list. In addition, if a list pattern contains an ellipsis, the ellipsis is not treated as a literal, instead it matches any number of duplications of the pattern that came before the ellipses (including 0). Furthermore, each `(name symbol pattern)` in the duplicated pattern binds a list of matches to `symbol`, instead of a single match. (A nested duplicated pattern creates a list of list matches, etc.) Ellipses may be placed anywhere inside the row of patterns, except in the first position or immediately after another ellipses.

Multiple ellipses are allowed. For example, this pattern:

```
((name x a) ... (name y a) ...)
```

matches this sexpression:

```
(term (a a))
```

three different ways. One where the first `a` in the pattern matches nothing, and the second matches both of the occurrences of `a`, one where each named pattern matches a single `a` and one where the first matches both and the second matches nothing.

If the ellipsis is named (ie, has an underscore and a name following it, like a variable may), the pattern matcher records the length of the list and ensures that any other occurrences of the same named ellipses must have the same length.

As an example, this pattern:

```
((name x a) ..._1 (name y a) ..._1)
```

only matches this sexpression:

```
(term (a a))
```

one way, with each named pattern matching a single `a`. Unlike the above, the two patterns with mismatched lengths is ruled out, due to the underscores following the ellipses.

Also, like underscore patterns above, if an underscore pattern begins with `...!_`, then the lengths must be different.

Thus, with the pattern:

```
((name x a) ...!_1 (name y a) ...!_1)
```

and the expression

```
(term (a a))
```

two matches occur, one where `x` is bound to `'()` and `y` is bound to `'(a a)` and one where `x` is bound to `'(a a)` and `y` is bound to `'()`.

```
(redex-match lang pattern any)
(redex-match lang pattern)
```

If `redex-match` receives three arguments, it matches the pattern (in the language) against its third argument. If it matches, this returns a list of match structures describing the matches (see `match?` and `match-bindings`). If it fails, it returns `#f`.

If `redex-match` receives only two arguments, it builds a procedure for efficiently testing if expressions match the pattern, using the language `lang`. The procedure accepts a single expression and if the expression matches, it returns a list of match structures describing the matches. If the match fails, the procedure returns `#f`.

Examples:

```
> (define-language nums
    (AE number
      (+ AE AE)))

> (redex-match nums
    (+ AE_1 AE_2)
    (term (+ (+ 1 2) 3)))
(list (match (list (bind 'AE_1 '(+ 1 2)) (bind 'AE_2 3))))
> (redex-match nums
    (+ AE_1 (+ AE_2 AE_3))
    (term (+ (+ 1 2) 3)))
#f
> (redex-match nums
    (+ AE_1 AE_1)
    (term (+ (+ 1 2) 3)))
#f
(redex-match? lang pattern any)
(redex-match? lang pattern)
```

Like `redex-match`, except it returns only a boolean indicating if the match was successful.

Examples:

```

> (define-language nums
  (AE number
    (+ AE AE)))

> (redex-match? nums
  (+ AE_1 AE_2)
  (term (+ (+ 1 2) 3)))

#t
> (redex-match? nums
  (+ AE_1 AE_1)
  (term (+ (+ 1 2) 3)))

#t
(match? val) → boolean?
  val : any/c

```

Determines if a value is a match structure.

```

(match-bindings m) → (listof bind?)
  m : match?

```

This returns a list of `bind` structs that binds the pattern variables in this match.

```

(struct bind (name exp)
  #:extra-constructor-name make-bind)
  name : symbol?
  exp : any/c

```

Instances of this struct are returned by `redex-match`. Each `bind` associates a name with an s-expression from the language, or a list of such s-expressions, if the `(name ...)` clause is followed by an ellipsis. Nested ellipses produce nested lists.

```

(caching-enabled?) → boolean?
(caching-enabled? on?) → void?
  on? : boolean?

```

When this parameter is `#t` (the default), Redex caches the results of pattern matching and metafunction evaluation. There is a separate cache for each pattern and metafunction; when one fills (see `set-cache-size!`), Redex evicts all of the entries in that cache.

Caching should be disabled when matching a pattern that depends on values other than the in-scope pattern variables or evaluating a metafunction that reads or writes mutable external state.

```

(set-cache-size! size) → void?
  size : positive-integer?

```

Changes the size of the per-pattern and per-metafunction caches.

The default size is 350.

```
(check-redundancy) → boolean?  
(check-redundancy check?) → void?  
  check? : boolean?
```

Ambiguous patterns can slow down Redex's pattern matching implementation significantly. To help debug such performance issues, set the `check-redundancy` parameter to `#t`. This causes Redex to, at runtime, report any redundant matches that it encounters.

## 2.2 Terms

Object language expressions in Redex are written using `term`. It is similar to Racket's `quote` (in many cases it is identical) in that it constructs lists as the visible representation of terms.

The grammar of *terms* is (note that an ellipsis stands for repetition unless otherwise indicated):

```
term = identifier  
      | (term-sequence ...)  
      | ,racket-expression  
      | (in-hole term term)  
      | hole  
      | #t  
      | #f  
      | string  
  
term-sequence = term  
              | ,@racket-expression  
              | ... ; literal ellipsis
```

- A term written `identifier` is equivalent to the corresponding symbol, unless the identifier is bound by `term-let`, `define-term`, or a pattern variable or the identifier is `hole` (as below).
- A term written `(term-sequence ...)` constructs a list of the terms constructed by the sequence elements.
- A term written `,racket-expression` evaluates the `racket-expression` and substitutes its value into the term at that point.
- A term written `,@racket-expression` evaluates the `racket-expression`, which must produce a list. It then splices the contents of the list into the expression at that point in the sequence.

- A term written `(in-hole tttterm tttterm)` is the dual to the pattern `in-hole` – it accepts a context and an expression and uses `plug` to combine them.
- A term written `hole` produces a hole.
- A term written as a literal boolean or a string produces the boolean or the string.

```
(term term)
(term term #:lang lang-id)
```

Used for construction of a term.

It behaves similarly to `quasiquote`, except for a few special forms that are recognized (listed below) and that names bound by `term-let` are implicitly substituted with the values that those names were bound to, expanding ellipses as in-place sublists (in the same manner as syntax-case patterns).

The optional `#:lang` keyword must supply an identifier bound by `define-language`, and adds a check that any symbol containing an underscore in `term` could have been bound by a pattern in the language referenced by `lang-id`. In practice, this means that the underscore must be preceded by a non-terminal in that language or a built-in *pattern* such as `number`. This form of `term` is used internally by default, so this check is applied to terms that are constructed by Redex forms such as `reduction-relation` and `define-metafunction`.

For example,

```
(term-let ([body '(+ x 1)]
          [(expr ...) '(+ - (values * /))]
          [(id ...) ...] '((a) (b) (c d))])
  (term (let-values ([id ...] expr) ...) body)))
```

evaluates to

```
'(let-values ([a +]
              [b -]
              [c d] (values * /)])
  (+ x 1))
```

It is an error for a term variable to appear in an expression with an ellipsis-depth different from the depth with which it was bound by `term-let`. It is also an error for two `term-let`-bound identifiers bound to lists of different lengths to appear together inside an ellipsis.

`hole`

Recognized specially within `term`. A `hole` form is an error elsewhere.

| in-hole

Recognized specially within reduction-relation. An in-hole form is an error elsewhere.

```
(term-let ([tl-pat expr] ...) body)  
  
    tl-pat = identifier  
           | (tl-pat-ele ...)  
  
tl-pat-ele = tl-pat  
           | tl-pat ... ; a literal ellipsis
```

Matches each given id pattern to the value yielded by evaluating the corresponding *expr* and binds each variable in the id pattern to the appropriate value (described below). These bindings are then accessible to the *term* syntactic form.

Note that each ellipsis should be the literal symbol consisting of three dots (and the ... elsewhere indicates repetition as usual). If *tl-pat* is an identifier, it matches any value and binds it to the identifier, for use inside *term*. If it is a list, it matches only if the value being matched is a list value and only if every subpattern recursively matches the corresponding list element. There may be a single ellipsis in any list pattern; if one is present, the pattern before the ellipses may match multiple adjacent elements in the list value (possibly none).

This form is a lower-level form in Redex, and not really designed to be used directly. For let-like forms that use Redex's full pattern matching facilities, see *redex-let*, *redex-let\**, *term-match*, *term-match/single*.

```
| (redex-let language ([pattern expression] ...) body ...+)
```

Like *term-let* but the left-hand sides are Redex patterns, interpreted according to the specified language. It is a syntax error for two left-hand sides to bind the same pattern variable.

This form raises an exception recognized by `exn:fail:redex?` if any right-hand side does not match its left-hand side in exactly one way.

In some contexts, it may be more efficient to use *term-match/single* (lifted out of the context).

```
| (redex-let* language ([pattern expression] ...) body ...+)
```

The *let\** analog of *redex-let*.

```
| (define-term identifier term)
```



Defines *identifier* for use in term templates.

```
(term-match language [pattern expression] ...)
```

This produces a procedure that accepts term (or quoted) expressions and checks them against each pattern. The function returns a list of the values of the expression where the pattern matches. If one of the patterns matches multiple times, the expression is evaluated multiple times, once with the bindings in the pattern for each match.

When evaluating a term-match expression, the patterns are compiled in an effort to speed up matching. Using the procedural result multiple times to avoid compiling the patterns multiple times.

```
(term-match/single language [pattern expression] ...)
```

This produces a procedure that accepts term (or quoted) expressions and checks them against each pattern. The function returns the expression behind the first successful match. If that pattern produces multiple matches, an error is signaled. If no patterns match, an error is signaled.

Raises an exception recognized by `exn:fail:redex?` if no clauses match or if one of the clauses matches multiple ways.

When evaluating a term-match/single expression, the patterns are compiled in an effort to speed up matching. Using the procedural result multiple times to avoid compiling the patterns multiple times.

```
(plug context expression) → any  
context : any/c  
expression : any/c
```

The first argument to this function is an s-expression to plug into. The second argument is the s-expression to replace in the first argument. It returns the replaced term. This is also used when a term sub-expression contains in-hole.

```
(variable-not-in t var) → symbol?  
t : any/c  
var : symbol?
```

This helper function accepts an s-expression and a variable. It returns a variable not in the s-expression with a prefix the same as the second argument.

```
(variables-not-in t vars) → (listof symbol?)  
t : any/c  
vars : (listof symbol?)
```

This function, like `variable-not-in`, makes variables that do not occur in its first argument, but it returns a list of such variables, one for each variable in its second argument.

Does not expect the input symbols to be distinct, but does produce variables that are always distinct.

```
(exn:fail:redex? v) → boolean?  
v : any/c
```

Returns `#t` if its argument is a Redex exception record, and `#f` otherwise.

## 2.3 Languages

```
(define-language lang-name  
  non-terminal-def ...)  
  
non-terminal-def = (non-terminal-name ...+ ::= pattern ...+)  
                  | (non-terminal-name pattern ...+)  
                  | ((non-terminal-name ...+) pattern ...+)
```

This form defines the grammar of a language. It allows the definition of recursive patterns, much like a BNF, but for regular-tree grammars. It goes beyond their expressive power, however, because repeated `name` patterns and side-conditions can restrict matches in a context-sensitive way.

A `non-terminal-def` comprises one or more non-terminal names (considered aliases) followed by one or more productions.

For example, the following defines `lc-lang` as the grammar of the  $\lambda$ -calculus:

```
(define-language lc-lang  
  (e (e e ...)  
      x  
      v)  
  (c (v ... c e ...)  
      hole)  
  (v ( $\lambda$  (x ...) e))  
  (x variable-not-otherwise-mentioned))
```

with non-terminals `e` for the expression language, `x` for variables, `c` for the evaluation contexts and `v` for values.

```
::=
```

A non-terminal's names and productions may be separated by the keyword `::=`. Use of the `::=` keyword outside a language definition is a syntax error.

```
(define-extended-language extended-lang base-lang
  non-terminal-def ...)

non-terminal-def = (non-terminal-name ...+ ::= pattern ...+)
                  | (non-terminal-name pattern ...+)
                  | ((non-terminal-name ...+) pattern ...+)
```

This form extends a language with some new, replaced, or extended non-terminals. For example, this language:

```
(define-extended-language lc-num-lang
  lc-lang
  (v ... ; extend the previous 'v' non-terminal
    number
    +)
  (x (variable-except λ +)))
```

extends *lc-lang* with two new alternatives (`+` and `number`) for the `v` non-terminal, carries forward the `e` and `c` non-terminals, and replaces the `x` non-terminal with a new one (which happens to be equivalent to the one that would have been inherited).

The four-period ellipses indicates that the new language's non-terminal has all of the alternatives from the original language's non-terminal, as well as any new ones. If a non-terminal occurs in both the base language and the extension, the extension's non-terminal replaces the originals. If a non-terminal only occurs in either the base language, then it is carried forward into the extension. And, of course, `extend-language` lets you add new non-terminals to the language.

If a language is has a group of multiple non-terminals defined together, extending any one of those non-terminals extends all of them.

```
(define-union-language L base/prefix-lang ...)

base/prefix-lang = lang-id
                  | (prefix lang-id)
```

Constructs a language that is the union of all of the languages listed in the *base/prefix-lang*.

If the two languages have non-terminals in common, then `define-union-language` will combine all of the productions of the common non-terminals. For example, this definition of *L*:

```

(define-language L1
  (e ::=
    (+ e e)
    number))
(define-language L2
  (e ::=
    (if e e e)
    true
    false))
(define-union-language L L1 L2)

```

is equivalent to this one:

```

(define-language L
  (e ::=
    (+ e e)
    number
    (if e e e)
    true
    false))

```

If a language has a prefix, then all of the non-terminals from that language have the corresponding prefix in the union language. The prefix helps avoid unintended collisions between the constituent language's non-terminals.

For example, with two these two languages:

```

(define-language UT
  (e (e e)
    (λ (x) e)
    x))
(define-language WT
  (e (e e)
    (λ (x t) e)
    x)
  (t (→ t t)
    num))

```

then this declaration:

```

(define-union-language B (ut. UT) (wt. WT))

```

will create a language named `B` containing the non-terminals `ut.e`, `wt.e`, and `wt.t` consisting of the productions listed in the original languages.

```
(language-nts lang) → (listof symbol?)  
  lang : compiled-lang?
```

Returns the list of non-terminals (as symbols) that are defined by this language.

```
(compiled-lang? l) → boolean?  
  l : any/c
```

Returns `#t` if its argument was produced by `language`, `#f` otherwise.

## 2.4 Reduction Relations

```
(reduction-relation language domain base-arrow  
  reduction-case ...  
  shortcuts)
```

```

    domain =
      | #:domain pattern

    base-arrow =
      | #:arrow base-arrow-name

    reduction-case = (arrow-name pattern term red-extras ...)

    red-extras = rule-name
      | (fresh fresh-clause ...)
      | (side-condition racket-expression)
      | (where pattern term)
      | (judgment-holds (judgment-form-id pat/term ...))
      | (side-condition/hidden racket-expression)
      | (where/hidden pattern term)

    shortcuts =
      | with shortcut ...

    shortcut = [(old-arrow-name pattern term)
                (new-arrow-name identifier identifier)]

    rule-name = identifier
      | string
      | (computed-name racket-expression)

    fresh-clause = var
      | ((var1 ...) (var2 ...))

    pat/term = pattern
      | term

```

Defines a reduction relation casewise, one case for each of the *reduction-case* clauses.

The optional *domain* clause provides a contract for the relation, in the form of a pattern that defines the relation's domain and codomain.

The *arrow-name* in each *reduction-case* clause is either *base-arrow-name* (default `-->`) or an arrow name defined by *shortcuts* (described below). In either case, the pattern refers to *language* and binds variables in the corresponding term. Following the pattern and term can be the name of the reduction rule and declarations of fresh variables and side-conditions.

For example, the expression

```
(reduction-relation
```

```

lc-lang
(--> (in-hole c_1 ((λ (variable_i ...) e_body) v_i ...))
      (in-hole c_1 ,(foldl lc-subst
                          (term e_body)
                          (term (v_i ...))
                          (term (variable_i ...))))))
      beta-v))

```

defines a reduction relation for the `lc-lang` grammar.

A rule's name (used in typesetting, the `stepper`, `traces`, and `apply-reduction-relation/tag-with-names`) can be given as a literal (an identifier or a string) or as an expression that computes a name using the values of the bound pattern variables (much like the rule's right-hand side). Some operations require literal names, so a rule definition may provide both a literal name and a computed name. In particular, only rules that include a literal name may be replaced using `extend-reduction-relation`, used as breakpoints in the `stepper`, and selected using `render-reduction-relation-rules`. The output of `apply-reduction-relation/tag-with-names`, `traces`, and the `stepper` prefers the computed name, if it exists. Typesetting a rule with a computed name shows the expression that computes the name only when the rule has no literal name or when it would not typeset in pink due to `with-unquote-rewriters` in the context; otherwise, the literal name (or nothing) is shown.

Fresh variable clauses generate variables that do not occur in the term being reduced. If the `fresh-clause` is a variable, that variable is used both as a binding in the term and as the prefix for the freshly generated variable. (The variable does not have to be a non-terminal in the language of the reduction relation.)

The second form of `fresh-clauses` generates a sequence of variables. In that case, the ellipses are literal ellipses; that is, you must actually write ellipses in your rule. The variable `var1` is like the variable in first case of a `fresh-clause`; namely it is used to determine the prefix of the generated variables and it is bound in the right-hand side of the reduction rule, but unlike the single-variable fresh clause, it is bound to a sequence of variables. The variable `var2` is used to determine the number of variables generated and `var2` must be bound by the left-hand side of the rule.

The expressions within `side-condition` clauses and `side-condition/hidden` clauses are collected with `and` and used as guards on the case being matched. The argument to each side-condition should be a Racket expression, and the pattern variables in the `pattern` are bound in that expression. A `side-condition/hidden` clause is the same as a `side-condition` clause, except that the condition is not rendered when typesetting via `redex/pict`.

Each `where clause` acts as a side condition requiring a successful pattern match, and it can bind pattern variables in the side-conditions (and `where` clauses) that follow and in the metafunction result. The bindings are the same as bindings in a `term-let` expression. A

`where/hidden` clause is the same as a `where` clause, but the clause is not rendered when typesetting via `redex/pict`.

Each judgment-holds clause acts like a `where` clause, where the left-hand side pattern incorporates each of the patterns used in the judgment form's output positions.

Each `shortcut` clause defines arrow names in terms of `base-arrow-name` and earlier `shortcut` definitions. The left- and right-hand sides of a `shortcut` definition are identifiers, not patterns and terms. These identifiers need not correspond to non-terminals in `language`.

For example, this expression

```
(reduction-relation
  lc-num-lang
  (==> ((λ (variable_i ...) e_body) v_i ...)
        ,(foldl lc-subst
                (term e_body)
                (term (v_i ...))
                (term (variable_i ...))))
  (==> (+ number_1 ...)
        ,(apply + (term (number_1 ...))))

  with
  [(-> (in-hole c_1 a) (in-hole c_1 b))
   (==> a b)])
```

defines reductions for the  $\lambda$ -calculus with numbers, where the `==>` shortcut is defined by reducing in the context `c`.

A fresh clause in `reduction-case` defined by shortcut refers to the entire term, not just the portion matched by the left-hand side of shortcut's use.

```
(extend-reduction-relation reduction-relation language more ...)
```

This form extends the reduction relation in its first argument with the rules specified in `more`. They should have the same shape as the rules (including the `with` clause) in an ordinary `reduction-relation`.

If the original reduction-relation has a rule with the same name as one of the rules specified in the extension, the old rule is removed.

In addition to adding the rules specified to the existing relation, this form also reinterprets the rules in the original reduction, using the new language.

```
(union-reduction-relations r ...) → reduction-relation?
  r : reduction-relation?
```



Combines all of the argument reduction relations into a single reduction relation that steps when any of the arguments would have stepped.

```
(reduction-relation->rule-names r) → (listof symbol?)  
r : reduction-relation?
```

Returns the names of the reduction relation's named clauses.

```
(compatible-closure reduction-relation lang non-terminal)
```

This accepts a reduction, a language, the name of a non-terminal in the language and returns the compatible closure of the reduction for the specified non-terminal.

```
(context-closure reduction-relation lang pattern)
```

This accepts a reduction, a language, a pattern representing a context (ie, that can be used as the first argument to `in-hole`; often just a non-terminal) in the language and returns the closure of the reduction in that context.

```
(reduction-relation? v) → boolean?  
v : any/c
```

Returns `#t` if its argument is a reduction-relation, and `#f` otherwise.

```
(apply-reduction-relation r t) → (listof any/c)  
r : reduction-relation?  
t : any/c
```

This accepts reduction relation, a term, and returns a list of terms that the term reduces to.

```
(apply-reduction-relation/tag-with-names r  
t)  
→ (listof (list/c (union false/c string?) any/c))  
r : reduction-relation?  
t : any/c
```

Like `apply-reduction-relation`, but the result indicates the names of the reductions that were used.

```
(apply-reduction-relation* r  
t  
[#:cache-all? cache-all?  
#:stop-when stop-when])  
→ (listof any/c)  
r : reduction-relation?  
t : any/c  
cache-all? : boolean? = (current-cache-all?)  
stop-when : (-> any/c any) = (λ (x) #f)
```

Accepts a reduction relation and a term. Starting from *t*, it follows every reduction path and returns all of the terms that do not reduce further. If there are infinite reduction sequences that do not repeat, this function will not terminate (it does terminate if the only infinite reduction paths are cyclic).

If the *cache-all?* argument is *#t*, then *apply-reduction-relation\** keeps a cache of all visited terms when traversing the graph and does not revisit any of them. This cache can, in some cases, use a lot of memory, so it is off by default and the cycle checking happens by keeping track only of the current path it is traversing through the reduction graph.

The *stop-when* argument controls the stopping criterion. Specifically, it is called with each term that *apply-reduction-relation\** encounters. If it ever returns a true value (anything except *#f*), then *apply-reduction-relation\** considers the term to be irreducible (and so returns it and does not try to reduce it further).

```
(current-cache-all?) → boolean?  
(current-cache-all? cache-all?) → void?  
  cache-all? : boolean?
```

Controls the behavior of *apply-reduction-relation\** and *test-->*'s cycle checking. See *apply-reduction-relation\** for more details.

Examples:

```
> (define-language empty-lang)  
  
> (define R  
  (reduction-relation  
    empty-lang  
    (--> 0 1)  
    (--> 0 2)  
    (--> 2 3)  
    (--> 3 3)))  
  
> (apply-reduction-relation R 0)  
'(2 1)  
> (apply-reduction-relation* R 0)  
'(1)
```

```
| -->
```

Recognized specially within *reduction-relation*. A *-->* form is an error elsewhere.

```
| fresh
```

Recognized specially within *reduction-relation*. A *fresh* form is an error elsewhere.

with

Recognized specially within `reduction-relation`. A `with` form is an error elsewhere.

## 2.5 Other Relations

```
(define-metafunction language
  metafunction-contract
  [(name pattern ...) term metafunction-extras ...]
  ...)

metafunction-contract =
  | id : pattern-sequence ... -> range
  | maybe-pre-condition

maybe-pre-condition = #:pre term
  |

range = pattern
  | pattern or range
  | pattern  $\vee$  range
  | pattern  $\cup$  range

metafunction-extras = (side-condition racket-expression)
  | (side-condition/hidden racket-expression)
  | (where pat term)
  | (where/hidden pat term)
  | (judgment-holds
     (judgment-form-id pat/term ...))
  | (clause-name name)
```

The `define-metafunction` form builds a function on sexpressions according to the pattern and right-hand-side expressions. The first argument indicates the language used to resolve non-terminals in the pattern expressions. Each of the rhs-expressions is implicitly wrapped in `term`.

The contract, if present, is matched against every input to the metafunction and, if the match fails, an exception is raised. If present, the term inside the `maybe-pre-condition` is evaluated after a successful match to the input pattern in the contract (with any variables from the input contract bound). If it returns `#f`, then the input contract is considered to not have matched and an error is also raised.

The `side-condition`, `hidden-side-condition`, `where`, and `where/hidden` clauses behave as in the `reduction-relation` form.

The resulting metafunction raises an exception recognized by `exn:fail:redex?` if no clauses match or if one of the clauses matches multiple ways (and that leads to different results for the different matches).

The `side-condition` extra is evaluated after a successful match to the corresponding argument pattern. If it returns `#f`, the clause is considered not to have matched, and the next one is tried. The `side-condition/hidden` extra behaves the same, but is not typeset.

The `where` and `where/hidden` extra are like `side-condition` and `side-condition/hidden`, except the match guards the clause.

The `judgment-holds` clause is like `side-condition` and `where`, except the given judgment must hold for the clause to be taken.

The `clause-name` is used only when typesetting. See `metafunction-cases`.

Note that metafunctions are assumed to always return the same results for the same inputs, and their results are cached, unless `caching-enabled?` is set to `#f`. Accordingly, if a metafunction is called with the same inputs twice, then its body is only evaluated a single time.

As an example, these metafunctions finds the free variables in an expression in the `lc-lang` above:

```
(define-metafunction lc-lang
  free-vars : e -> (x ...)
  [(free-vars (e_1 e_2 ...))
   (U (free-vars e_1) (free-vars e_2) ...)]
  [(free-vars x) (x)]
  [(free-vars (λ (x ...) e))
   (- (free-vars e) (x ...))])
```

The first argument to `define-metafunction` is the grammar (defined above). Following that are three cases, one for each variation of expressions (`e` in `lc-lang`). The free variables of an application are the free variables of each of the subterms; the free variables of a variable is just the variable itself, and the free variables of a  $\lambda$  expression are the free variables of the body, minus the bound parameters.

Here are the helper metafunctions used above.

```
(define-metafunction lc-lang
  U : (x ...) ... -> (x ...)
  [(U (x_1 ...) (x_2 ...) (x_3 ...) ...)
   (U (x_1 ... x_2 ...) (x_3 ...) ...)]
  [(U (x_1 ...))
   (x_1 ...)]
  [(U) ()])
```

```
(define-metafunction lc-lang
  - : (x ...) (x ...) -> (x ...)
  [(- (x ...) ()) (x ...)]
  [(- (x_1 ... x_2 x_3 ...) (x_2 x_4 ...))
   (- (x_1 ... x_3 ...) (x_2 x_4 ...))
   (side-condition (not (memq (term x_2) (term (x_3 ...))))))]
  [(- (x_1 ...) (x_2 x_3 ...))
   (- (x_1 ...) (x_3 ...))])
```

Note the side-condition in the second case of `-`. It ensures that there is a unique match for that case. Without it, `(term (- (x x) x))` would lead to an ambiguous match.

```
(define-metafunction/extension f language
  metafunction-contract
  [(g pattern ...) term metafunction-extras ...]
  ...)
```

Defines a metafunction `g` as an extension of an existing metafunction `f`. The metafunction `g` behaves as if `f`'s clauses were appended to its definition (with occurrences of `f` changed to `g` in the inherited clauses).

For example, `define-metafunction/extension` may be used to extend the `free-vars` function above to the forms introduced by the language `lc-num-lang`.

```
(define-metafunction/extension free-vars lc-num-lang
  free-vars-num : e -> (x ...)
  [(free-vars-num number)
   ()]
  [(free-vars-num (+ e_1 e_2))
   (∪ (free-vars-num e_1)
       (free-vars-num e_2))])
```

```
(in-domain? (metafunction-name term ...))
```

Returns `#t` if the inputs specified to `metafunction-name` are legitimate inputs according to `metafunction-name`'s contract, and `#f` otherwise.

```
(define-judgment-form language
  mode-spec
  contract-spec
  rule rule ...)
```

```

mode-spec = #:mode (form-id pos-use ...)

contract-spec =
  | #:contract (form-id pattern-sequence ...)

pos-use = I
         | 0

rule = [premise
        ...
        dashes rule-name
        conclusion]
      | [conclusion
        premise
        ...
        rule-name]

conclusion = (form-id pat/term ...)

premise = (judgment-form-id pat/term ...) maybe-ellipsis
         | (where pattern term)
         | (where/hidden pattern term)
         | (side-condition term)
         | (side-condition/hidden term)

rule-name =
  | string
  | non-ellipsis-non-hypens-var

pat/term = pattern
         | term

maybe-ellipsis =
  | ...

dashes = ---
        | ----
        | -----
        | etc.

```

Defines *form-id* as a relation on terms via a set of inference rules. Each rule must be such that its premises can be evaluated left-to-right without “guessing” values for any of their pattern variables. Redex checks this property using the mandatory *mode-spec* declaration, which partitions positions into inputs I and outputs O. Output positions in conclusions and input positions in premises must be *terms*; input positions in conclusions and output po-

sitions in premises must be *patterns*. When the optional *contract-spec* declaration is present, Redex dynamically checks that the terms flowing through these positions match the provided patterns, raising an exception recognized by `exn:fail:redex` if not.

For example, the following defines addition on natural numbers:

```
> (define-language nats
    (n ::= z (s n)))

> (define-judgment-form nats
    #:mode (sum I I 0)
    #:contract (sum n n n)
    [----- "zero"
     (sum z n n)]

    [(sum n_1 n_2 n_3)
     ----- "add1"
     (sum (s n_1) n_2 (s n_3))])
```

The `judgment-holds` form checks whether a relation holds for any assignment of pattern variables in output positions.

Examples:

```
> (judgment-holds (sum (s (s z)) (s z) (s (s (s z)))))
#t
> (judgment-holds (sum (s (s z)) (s z) (s (s (s n)))))
#t
> (judgment-holds (sum (s (s z)) (s z) (s (s (s (s n)))))
#f
```

Alternatively, this form constructs a list of terms based on the satisfying pattern variable assignments.

Examples:

```
> (judgment-holds (sum (s (s z)) (s z) (s (s (s n))))) n)
'(z)
> (judgment-holds (sum (s (s z)) (s z) (s (s (s (s n))))) n)
'()
> (judgment-holds (sum (s (s z)) (s z) (s (s (s n))))) (s n))
'((s z))
```

Declaring different modes for the same inference rules enables different forms of computation. For example, the following mode allows `judgment-holds` to compute all pairs with a given sum.

```

> (define-judgment-form nats
  #:mode (sumr 0 0 I)
  #:contract (sumr n n n)
  [-----
   (sumr z n n)]

  [(sumr n_1 n_2 n_3)
   -----
   (sumr (s n_1) n_2 (s n_3))])

> (judgment-holds (sumr n_1 n_2 (s (s z))) (n_1 n_2))
'(((s (s z)) z) ((s z) (s z)) (z (s (s z))))

```

A rule's `where` and `where/hidden` premises behave as in `reduction-relation` and `define-metafunction`.

Examples:

```

> (define-judgment-form nats
  #:mode (le I I)
  #:contract (le n n)
  [-----
   (le z n)]

  [(le n_1 n_2)
   -----
   (le (s n_1) (s n_2))])

> (define-metafunction nats
  pred : n -> n or #f
  [(pred z) #f]
  [(pred (s n)) n])

> (define-judgment-form nats
  #:mode (gt I I)
  #:contract (gt n n)
  [(where n_3 (pred n_1))
   (le n_2 n_3)
   -----
   (gt n_1 n_2)])

> (judgment-holds (gt (s (s z)) (s z)))
#t
> (judgment-holds (gt (s z) (s z)))
#f

```



A rule's `side-condition` and `side-condition/hidden` premises are similar to those in `reduction-relation` and `define-metafunction`, except that they do not implicitly unquote their right-hand sides. In other words, a premise of the form `(side-condition term)` is equivalent to the premise `(where #t term)`, except it does not typeset with the “#t =”, as that would.

Judgments with exclusively I mode positions may also be used in `terms` in a manner similar to metafunctions, and evaluate to a boolean.

Examples:

```
> (term (le (s z) (s (s z))))
#t
> (term (le (s z) z))
#f
```

A literal ellipsis may follow a judgment premise when a template in one of the judgment's input positions contains a pattern variable bound at ellipsis-depth one.

Examples:

```
> (define-judgment-form nats
  #:mode (even I)
  #:contract (even n)

  [----- "evenz"
   (even z)]

  [(even n)
   ----- "even2"
   (even (s (s n)))]

> (define-judgment-form nats
  #:mode (all-even I)
  #:contract (all-even (n ...))
  [(even n) ...
   -----
   (all-even (n ...))]

> (judgment-holds (all-even (z (s (s z)) z)))
#t
> (judgment-holds (all-even (z (s (s z)) (s z))))
#f
```

Redex evaluates premises depth-first, even when it doing so leads to non-termination. For example, consider the following definitions:

```

> (define-language vertices
  (v a b c))

> (define-judgment-form vertices
  #:mode (edge I 0)
  #:contract (edge v v)
  [(edge a b)]
  [(edge b c)])

> (define-judgment-form vertices
  #:mode (path I I)
  #:contract (path v v)
  [-----
   (path v v)]

  [(path v_2 v_1)
   -----
   (path v_1 v_2)]

  [(edge v_1 v_2)
   (path v_2 v_3)
   -----
   (path v_1 v_3)])

```

Due to the second `path` rule, the follow query fails to terminate:

```
> (judgment-holds (path a c))
```

The "examples" directory demonstrates three use cases:

- "typing-rules.rkt" — defines a type system in a way that supports mechanized typesetting. When a typing judgment form can be given a mode, it can also be encoded as a metafunction using `where` clauses as premises, but Redex cannot typeset that encoding as inference rules.
- "sos.rkt" — defines an SOS-style semantics in a way that supports mechanized typesetting.
- "multi-val.rkt" — defines a judgment form that serves as a multi-valued metafunction.

```

(define-extended-judgment-form language judgment-form-id
  option ...
  rule ...)

```

Defines a new judgment form that extends *judgment-form-id* with additional rules. The *options* and *rules* are as in `define-judgment-form`.

The mode specification in this judgment form and the original must be the same.

```
(judgment-holds judgment)
(judgment-holds judgment term)

judgment = (judgment-form-id pat/term ...)
```

In its first form, checks whether *judgment* holds for any assignment of the pattern variables in *judgment-id*'s output positions. In its second form, produces a list of terms by instantiating the supplied term template with each satisfying assignment of pattern variables. See `define-judgment-form` for examples.

```
(build-derivations judgment)
```

Constructs all of the `derivation` trees for *judgment*.

Example:

```
> (build-derivations (even (s (s z))))
(list
 (derivation
  '(even (s (s z)))
  "even2"
  (list (derivation '(even z) "evenz" '()))))

(struct derivation (term name subs)
 #:extra-constructor-name make-derivation)
 term : any/c
 name : (or/c string? #f)
 subs : (listof derivation?)
```

Represents a derivation from a judgment form.

The `term` field holds an s-expression based rendering of the conclusion of the derivation, the `name` field holds the name of the clause with `term` as the conclusion, and `subs` contains the sub-derivations.

See also `build-derivations`.

I

Recognized specially within `define-judgment-form`, the `I` keyword is an error elsewhere.

0

Recognized specially within `define-judgment-form`, the `0` keyword is an error elsewhere.

```
(define-relation language
  relation-contract
  [(name pattern ...)
   term ...
   metafunction-extras ...] ...)

relation-contract =
  | form-id  $\subseteq$  pattern x ... x pattern
  | form-id  $\subseteq$  pattern  $\times$  ...  $\times$  pattern
```

Similar to `define-judgment-form` but suitable only when every position is an input. There is no associated form corresponding to `judgment-holds`; querying the result uses the same syntax as metafunction application.

The contract specification for a relation restricts the patterns that can be used as input to a relation. For each argument to the relation, there should be a single pattern, using `x` or  `$\times$`  to separate the argument contracts.

Examples:

```
> (define-language types
  (( $\tau$   $\sigma$ ) int
   num
   ( $\tau \rightarrow \tau$ )))

> (define-relation types
  subtype  $\subseteq$   $\tau \times \tau$ 
  [(subtype int num)]
  [(subtype ( $\tau_1 \rightarrow \tau_2$ ) ( $\sigma_1 \rightarrow \sigma_2$ ))
   (subtype  $\sigma_1 \tau_1$ )
   (subtype  $\tau_2 \sigma_2$ )]
  [(subtype  $\tau \tau$ )])

> (term (subtype int num))
#t
> (term (subtype (int  $\rightarrow$  int) (num  $\rightarrow$  num)))
#f
> (term (subtype (num  $\rightarrow$  int) (num  $\rightarrow$  num)))
#t
(current-traced-metafunctions)  $\rightarrow$  (or/c 'all (listof symbol?))
(current-traced-metafunctions traced-metafunctions)  $\rightarrow$  void?
traced-metafunctions : (or/c 'all (listof symbol?))
```

Controls which metafunctions are currently being traced. If it is `'all`, all of them are. Otherwise, the elements of the list name the metafunctions to trace.

The tracing looks just like the tracing done by the `racket/trace` library, except that the first column printed by each traced call indicate if this call to the metafunction is cached. Specifically, a `c` is printed in the first column if the result is just returned from the cache and a space is printed if the metafunction call is actually performed.

Defaults to `'()`.

## 2.6 Testing

```
(test-equal e1 e2)
```

Tests to see if `e1` is equal to `e2`.

```
(test-->> rel-expr option ... e1-expr e2-expr ...)  
  
option = #:cycles-ok  
        | #:equiv pred-expr  
        | #:pred pred-expr  
  
rel-expr : reduction-relation?  
pred-expr : (--> any/c any)  
e1-expr  : any/c  
e2-expr  : any/c
```

Tests to see if the term `e1-expr`, reduces to the terms `e2-expr` under `rel-expr`, using `pred-expr` to determine equivalence.

If `#:pred` is specified, it is applied to each reachable term until one of the terms fails to satisfy the predicate (i.e., the predicate returns `#f`). If that happens, then the test fails and a message is printed with the term that failed to satisfy the predicate.

This test uses `apply-reduction-relation*`, so it does not terminate when the resulting reduction graph is infinite, although it does terminate if there are cycles in the (finite) graph.

If `#:cycles-ok` is not supplied then any cycles detected are treated as a test failure. If a `pred-expr` is supplied, then it is used to compare the expected and actual results.

```
(test--> rel-expr option ... e1-expr e2-expr ...)  
  
option = #:equiv pred-expr
```

```

rel-expr : reduction-relation?
pred-expr : (--> any/c any/c any/c)
e1-expr : any/c
e2-expr : any/c

```

Tests to see if the term *e1-expr*, reduces to the terms *e2-expr* in a single *rel-expr* step, using *pred-expr* to determine equivalence.

Examples:

```

> (define-language L
  (i integer))

> (define R
  (reduction-relation
   L
   (--> i i)
   (--> i ,(add1 (term i)))))

> (define (mod2=? i j)
  (= (modulo i 2) (modulo j 2)))

> (test--> R #:equiv mod2=? 7 1)
FAILED :46.0
expected: 1
actual: 8
actual: 7

> (test--> R #:equiv mod2=? 7 1 0)

> (test-results)
1 test failed (out of 2 total).

```

```

(test-->> option ... rel-expr start-expr goal-expr)

option = #:steps steps-expr

rel-expr : reduction-relation?
start-expr : any/c
goal-expr : (or/c (-> any/c any/c)
              (not/c procedure?))
steps-expr : (or/c natural-number/c +inf.0)

```

Tests to see if the term *start-expr* reduces according to the reduction relation *rel-expr*

to a term specified by *goal-expr* in *steps-expr* or fewer steps (default 1,000). The specification *goal-expr* may be either a predicate on terms or a term itself.

```
| test-->>E
```

An alias for `test-->>∃`.

Examples:

```
> (define-language L
    (n natural))

> (define succ-mod8
    (reduction-relation
     L
     (--> n ,(modulo (add1 (term n)) 8))))

> (test-->>∃ succ-mod8 6 2)

> (test-->>∃ succ-mod8 6 even?)

> (test-->>∃ succ-mod8 6 8)
FAILED :53.0
term 8 not reachable from 6

> (test-->>∃ #:steps 6 succ-mod8 6 5)
FAILED :54.0
term 5 not reachable from 6 (within 6 steps)

> (test-results)
2 tests failed (out of 4 total).
```

```
| (test-predicate p? e)
```

Tests to see if the value of *e* matches the predicate *p?*.

```
| (test-results) → void?
```

Prints out how many tests passed and failed, and resets the counters so that next time this function is called, it prints the test results for the next round of tests.

```
| (make-coverage subject)
|
| subject = metafunction
|          | relation-expr
```

Constructs a structure (recognized by `coverage?`) to contain per-case test coverage of the supplied metafunction or reduction relation. Use with `relation-coverage` and `covered-cases`.

```
(coverage? v) → boolean?  
v : any/c
```

Returns `#t` for a value produced by `make-coverage` and `#f` for any other.

```
(relation-coverage) → (listof coverage?)  
(relation-coverage tracked) → void?  
tracked : (listof coverage?)
```

Redex populates the coverage records in `tracked` (default `null`), counting the times that tests exercise each case of the associated metafunction and relations.

```
(covered-cases c) → (listof (cons/c string? natural-number/c))  
c : coverage?
```

Extracts the coverage information recorded in `c`, producing an association list mapping names (or source locations, in the case of metafunctions or unnamed reduction-relation cases) to application counts.

Examples:

```
> (define-language empty-lang)  
  
> (define-metafunction empty-lang  
  [(plus number_1 number_2)  
   ,(+ (term number_1) (term number_2))])  
  
> (define equals  
  (reduction-relation  
   empty-lang  
   (--> (+) 0 "zero")  
   (--> (+ number) number)  
   (--> (+ number_1 number_2 number ...)   
        (+ (plus number_1 number_2)  
           number ...)  
        "add")))   
  
> (let ([equals-coverage (make-coverage equals)]  
      [plus-coverage (make-coverage plus)])  
  (parameterize ([relation-coverage (list equals-coverage  
                                         plus-coverage)])  
    (apply-reduction-relation* equals (term (+ 1 2 3))))
```



```

      (values (covered-cases equals-coverage)
              (covered-cases plus-coverage))))
'(("#f:58:0" . 1) ("add" . 2) ("zero" . 0))
'(("#f:57:0" . 2))
(generate-term from-pattern)
(generate-term from-judgment-form)
(generate-term from-metafunction)
(generate-term from-reduction-relation)

from-pattern = language pattern size-expr kw-args ...
              | language pattern
              | language pattern #:i-th index-expr
              | language pattern #:i-th

from-judgment-form = language #:satisfying
                    (judgment-form-id pattern ...)
                    | language #:satisfying
                    (judgment-form-id pattern ...)
                    size-expr

from-metafunction = language #:satisfying
                   (metafunction-id pattern ...) = pattern
                   | language #:satisfying
                   (metafunction-id pattern ...) = pattern
                   size-expr
                   | #:source metafunction size-expr kw-args
                   | #:source metafunction

from-reduction-relation = #:source reduction-relation-expr
                          size-expr kw-args ...
                          | #:source reduction-relation-expr

kw-args = #:attempt-num attempts-expr
          | #:retries retries-expr

size-expr : natural-number/c
attempt-num-expr : natural-number/c
retries-expr : natural-number/c

```

Generates terms in a number of different ways:

- *from-pattern*: In the first case, randomly makes an expression matching the given pattern whose size is bounded by *size-expr*; the second returns a function that accepts a size bound and returns a random term. Calling this function (even with the same size bound) may be more efficient than using the first case.

Examples:

```
> (define-language L
    (e ::=
      (e e)
      (λ (x) e)
      x)
    (x ::= a b c))

> (for/list ([i (in-range 10)])
    (generate-term L e 3))
'( (b (b (c c)))
  (λ (b) ((λ (c) b) (c b)))
  ((λ (b) b) a)
  ((λ (b) (λ (c) b)) (λ (b) (c c)))
  (((b a) (λ (c) c)) (λ (a) b))
  b
  (b (λ (b) (λ (b) a)))
  ((λ (a) b) ((λ (b) b) (λ (a) b)))
  c
  b)
```

The `#:i-th` option uses an enumeration of the non-terminals in a language. If *index-expr* is supplied, `generate-term` returns the corresponding term and if it isn't, `generate-term` returns a function from indices to terms.

Example:

```
> (for/list ([i (in-range 9)])
    (generate-term L e #:i-th i))
'(a (a a) b (λ (a) a) c (a (a a)) (λ (b) a) ((a a) a) (λ (c)
a))
```

Base type enumerations such as `boolean`, `natural` and `integer` are what you might expect:

Examples:

```
> (for/list ([i (in-range 10)])
    (generate-term L boolean #:i-th i))
'(#t #f #t #f #t #f #t #f #t #f)
> (for/list ([i (in-range 10)])
    (generate-term L natural #:i-th i))
'(0 1 2 3 4 5 6 7 8 9)
> (for/list ([i (in-range 10)])
    (generate-term L integer #:i-th i))
'(0 1 -1 2 -2 3 -3 4 -4 5)
```

The `real` base type enumeration consists of all integers and flonums, and the `number` pattern consists of complex numbers with real and imaginary parts taken from the `real` enumeration.

Examples:

```
> (for/list ([i (in-range 20)])
      (generate-term L real #:i-th i))
'(0
  +inf.0
  1
  -inf.0
  -1
  +nan.0
  2
  0.0
  -2
  4.9406564584125e-324
  3
  -4.9406564584125e-324
  -3
  9.8813129168249e-324
  4
  -9.8813129168249e-324
  -4
  1.4821969375237e-323
  5
  -1.4821969375237e-323)
> (for/list ([i (in-range 20)])
      (generate-term L number #:i-th i))
'(0
  0+inf.0i
  +inf.0
  0+1i
  1
  +inf.0+inf.0i
  -inf.0
  0-inf.0i
  -1
  +inf.0+1.0i
  +nan.0
  1.0+inf.0i
  2
  0-1i
  0.0
  +inf.0-inf.0i
  -2)
```

```
1+i
4.9406564584125e-324
-inf.0+inf.0i)
```

The `string` enumeration produces all single character strings before going on to strings with multiple characters. For each character it starts the lowercase Latin characters, then uppercase Latin, and then every remaining Unicode character. The `variable` enumeration is the same, except it produces symbols instead of strings.

Examples:

```
> (generate-term L string #:i-th 0)
""
> (generate-term L string #:i-th 1)
"a"
> (generate-term L string #:i-th 26)
"z"
> (generate-term L string #:i-th 27)
"A"
> (generate-term L string #:i-th 52)
"Z"
> (generate-term L string #:i-th 53)
"\u0000"
> (generate-term L string #:i-th 956)
"λ"
> (generate-term L variable #:i-th 1)
'a
> (generate-term L variable #:i-th 27)
'A
```

The `variable-prefix`, `variable-except`, and `variable-not-otherwise-mentioned` are defined similarly, as you expect.

Examples:

```
> (define-language L
  (used ::= a b c)
  (except ::= (variable-except a))
  (unused ::= variable-not-otherwise-mentioned))

> (for/list ([i (in-range 10)])
  (generate-term L (variable-prefix a:) #:i-th i))
'(a: a:a a:b a:c a:d a:e a:f a:g a:h a:i)
> (for/list ([i (in-range 10)])
  (generate-term L except #:i-th i))
'(| b c d e f g h i j)
> (for/list ([i (in-range 10)])
  (generate-term L unused #:i-th i))
```

```
'(| d e f g h i j k l)
```

Finally, the any pattern enumerates sexpressions of the above base-types.

Example:

```
> (for/list ([i (in-range 20)])
      (generate-term L any #:i-th i))
'(()
  (())
  0
  (())
  ""
  (((()))
  0+inf.0i
  (()) . 0)
  #t
  (((()) ())
  +inf.0
  (0)
  "a"
  (()) () ())
  0+1i
  (((()) . 0)
  ||
  (0 ()))
  1
  (((() ())))
```

In addition, all other pattern types are supported except for mismatch `!_` patterns, mismatch repeat `...!_` patterns and `side-condition` patterns.

The enumerators do not repeat terms unless the given pattern is ambiguous. Roughly speaking, the enumerator generates all possible ways that a pattern might be parsed and since ambiguous patterns have multiple ways they might be parsed, those multiple parsings turn into repeated elements in the enumeration.

Example:

```
> (for/list ([i (in-range 9)])
      (generate-term L (boolean_1 ... boolean_2 ...) #:i-th i))
'(() (#t) (#t) (#f) (#t #t) (#f) (#t #t) (#t #f) (#f #t))
```

Other sources of ambiguity are in-hole and overlapping non-terminals.

Examples:

```
> (define-language L
      (e ::= (e e) (λ (x) e) x)
      (E ::= hole (e E) (E e))
      (x ::= a b c))
```

```

> (for/list ([i (in-range 9)])
      (generate-term L (in-hole E e) #:i-th i))
'(a (a a) (a a) b (a (a a)) (a a) (λ (a) a) (a b) ((a a) a))
> (define-language L
      (overlap ::= natural integer))

> (for/list ([i (in-range 10)])
      (generate-term L overlap #:i-th i))
'(0 0 1 1 2 -1 3 2 4 -2)

```

- *from-judgment-form*: Randomly picks a term that satisfies the given use of the judgment form.

Examples:

```

> (define-language L
      (nat ::= Z (S nat)))

> (define-judgment-form L
      #:mode (sum I I 0)
      [-----
        (sum Z nat nat)]
      [(sum nat_1 nat_2 nat_3)
       -----
        (sum (S nat_1) nat_2 (S nat_3))])

> (for/list ([i (in-range 10)])
      (generate-term L #:satisfying
        (sum nat_1 nat_2 nat_3)
        3))
'((sum Z Z Z)
  (sum (S (S (S Z))) Z (S (S (S Z))))
  (sum (S Z) (S Z) (S (S Z)))
  (sum Z Z Z)
  (sum Z Z Z)
  (sum (S Z) (S Z) (S (S Z)))
  (sum (S (S Z)) Z (S (S Z)))
  (sum (S Z) Z (S Z))
  (sum Z (S (S Z)) (S (S Z)))
  (sum (S (S (S Z))) Z (S (S (S Z)))))

```

- *from-metafunction*: The first form randomly picks a term that satisfies the given invocation of the metafunction, using techniques similar to how the *from-judgment-form* case works. The second form uses a more naive approach; it simply generates terms that match the patterns of the cases of the metafunction; it does not consider the results of the metafunctions, nor does it consider patterns from earlier cases when

generating terms based on a particular case. The third case is like the second, except it returns a function that accepts the size and keywords arguments that may be more efficient if multiple random terms are generated.

Examples:

```
> (define-language L
    (n number))

> (define-metafunction L
    [(F one-clause n) ()]
    [(F another-clause n) ()])

> (for/list ([i (in-range 10)])
    (generate-term #:source F 5))
'((another-clause 2)
  (one-clause 1)
  (another-clause 2)
  (another-clause 0)
  (one-clause 1)
  (one-clause 4)
  (another-clause 0)
  (one-clause 4)
  (another-clause 0)
  (one-clause 2))
```

- *from-reduction-relation*: In the first case, `generate-term` randomly picks a rule from the reduction relation and tries to pick a term that satisfies its domain pattern, returning that. The second case returns a function that accepts the size and keyword arguments that may be more efficient if multiple random terms are generated.

Examples:

```
> (define-language L
    (n number))

> (for/list ([i (in-range 10)])
    (generate-term
     #:source
     (reduction-relation
      L
      (--> (one-clause n) ())
      (--> (another-clause n) ()))
     5))
'((one-clause 1)
  (one-clause 0)
  (another-clause 0)
  (another-clause 0))
```

```

(another-clause 2)
(one-clause 0)
(one-clause 2)
(one-clause 3)
(another-clause 2)
(another-clause 3))

```

The argument *size-expr* bounds the height of the generated term (measured as the height of its parse tree).

The optional keyword argument *attempt-num-expr* (default 1) provides coarse grained control over the random decisions made during generation; increasing *attempt-num-expr* tends to increase the complexity of the result. For example, the absolute values of numbers chosen for integer patterns increase with *attempt-num-expr*.

The random generation process does not actively consider the constraints imposed by side-condition or `_!_` patterns; instead, it uses a “guess and check” strategy in which it freely generates candidate terms then tests whether they happen to satisfy the constraints, repeating as necessary. The optional keyword argument *retries-expr* (default 100) bounds the number of times that `generate-term` retries the generation of any pattern. If `generate-term` is unable to produce a satisfying term after *retries-expr* attempts, it raises an exception recognized by `exn:fail:redex:generation-failure?`.

```

(redex-check template property-expr kw-arg ...)

template = language pattern
           | language pattern #:enum enum-expr
           | language #:satisfying
             (judgment-form-id pattern ...)
           | language #:satisfying
             (metafunction-id pattern ...) = pattern

kw-arg = #:attempts attempts-expr
          | #:source metafunction
          | #:source relation-expr
          | #:retries retries-expr
          | #:print? print?-expr
          | #:attempt-size attempt-size-expr
          | #:prepare prepare-expr
          | #:keep-going? keep-going?-expr

```



```

property-expr : any/c
attempts-expr : natural-number/c
relation-expr : reduction-relation?
retries-expr : natural-number/c
print?-expr : any/c
attempt-size-expr : (-> natural-number/c natural-number/c)
prepare-expr : (-> any/c any/c)

```

Searches for a counterexample to `property-expr`, interpreted as a predicate universally quantified over the pattern variables bound by the `pattern(s)` in `template`. `redex-check` constructs and tests a candidate counterexample by choosing a random term `t` based on `template` and then evaluating `property-expr` using the `match-bindings` produced by matching `t` against `pattern`. The form of `template` controls how `t` is generated:

- `language pattern`: In this case, `redex-check` randomly generates terms that match `pattern`.
- `language pattern`: In this case, `redex-check` uniformly at random picks a number less than the value of `enum-expr` (which must be a non-negative integer) and then uses that to index into an enumeration of `pattern`.
- `language #:satisfying (judgment-form-id pattern ...)`: Generates terms that match `pattern` and satisfy the judgment form.
- `language #:satisfying (metafunction-id pattern ...) = pattern`: Generates terms matching the two `patterns`, such that if the first is the argument to the metafunction, the second will be the result.

`redex-check` generates at most `attempts-expr` (default `(default-check-attempts)`) random terms in its search. The size and complexity of these terms tend to increase with each failed attempt. The `#:attempt-size` keyword determines the rate at which terms grow by supplying a function that bounds term size based on the number of failed attempts (see `generate-term`'s `size-expr` argument). By default, the bound grows according to the `default-attempt-size` function.

When `print?-expr` produces any non-`#f` value (the default), `redex-check` prints the test outcome on `current-output-port`. When `print?-expr` produces `#f`, `redex-check` prints nothing, instead

- returning a `counterexample` structure when the test reveals a counterexample,
- returning `#t` when all tests pass, or
- raising a `exn:fail:redex:test` when checking the property raises an exception.

The optional `#:prepare` keyword supplies a function that transforms each generated example before `redex-check` checks *property-expr*. This keyword may be useful when *property-expr* takes the form of a conditional, and a term chosen freely from the grammar is unlikely to satisfy the conditional's hypothesis. In some such cases, the `prepare` keyword can be used to increase the probability that an example satisfies the hypothesis.

The `#:retries` keyword behaves identically as in `generate-term`, controlling the number of times the generation of any pattern will be reattempted. It can't be used together with `#:satisfying`.

If *keep-going?-expr* produces any non-`#f` value, `redex-check` will stop only when it hits the limit on the number of attempts showing all of the errors it finds. This argument is allowed only when *print?-expr* is not `#f`.

When passed a metafunction or reduction relation via the optional `#:source` argument, `redex-check` distributes its attempts across the left-hand sides of that metafunction/relation by using those patterns, rather than `pattern`, as the basis of its generation. It is an error if any left-hand side generates a term that does not match `pattern`. `#:source` cannot be used with `#:satisfying`.

Examples:

```
> (define-language empty-lang)

> (random-seed 0)

> (redex-check
  empty-lang
  ((number_1 ...)
   (number_2 ...))
  (equal? (reverse (append (term (number_1 ...))
                           (term (number_2 ...))))
          (append (reverse (term (number_1 ...)))
                  (reverse (term (number_2 ...))))))
redex-check: counterexample found after 5 attempts:
((1 0) (0))

> (redex-check
  empty-lang
  ((number_1 ...)
   (number_2 ...))
  (equal? (reverse (append (term (number_1 ...))
                           (term (number_2 ...))))
          (append (reverse (term (number_2 ...)))
                  (reverse (term (number_1 ...))))))
  #:attempts 200)
redex-check: no counterexamples in 200 attempts
```

```

> (let ([R (reduction-relation
            empty-lang
            (--> ( $\Sigma$ ) 0)
            (--> ( $\Sigma$  number) number)
            (--> ( $\Sigma$  number_1 number_2 number_3 ...)
                ( $\Sigma$  ,(+ (term number_1) (term number_2))
                    number_3 ...)))]])
    (redex-check
     empty-lang
     ( $\Sigma$  number ...)
     (printf "~s\n" (term (number ...)))
     #:attempts 3
     #:source R))
()
(1)
(3 0)
redex-check: no counterexamples in 1 attempt (with each clause)

> (redex-check
  empty-lang
  number
  (begin
    (printf "checking ~s\n" (term number))
    (positive? (term number)))
  #:prepare ( $\lambda$  (n)
            (printf "preparing ~s; " n)
            (add1 (abs n)))
  #:attempts 3)
preparing 0; checking 1
preparing 0; checking 1
preparing 1; checking 2
redex-check: no counterexamples in 3 attempts

> (define-language L
    (nat ::= Z (S nat)))

> (define-judgment-form L
    #:mode (sum I I 0)
    [-----
     (sum Z nat nat)]
    [(sum nat_1 nat_2 nat_3)
     -----
     (sum (S nat_1) nat_2 (S nat_3))])

> (redex-check L

```

```

      #:satisfying
      (sum nat_1 nat_2 nat_3)
      (equal? (judgment-holds
              (sum nat_1 nat_2 nat_4) nat_4)
              (term (nat_3)))
      #:attempts 100)
redex-check: no counterexamples in 100 attempts

```

```

> (redex-check L
   #:satisfying
   (sum nat_1 nat_2 nat_3)
   (equal? (term nat_1) (term nat_2)))
redex-check: counterexample found after 1 attempt:
(sum Z (S Z) (S Z))

```

```

(redex-generator language-id satisfying size-expr)

satisfying = (judgment-form-id pattern ...)
             | (metafunction-id pattern ...) = pattern

size-expr : natural-number/c

```

**WARNING:** *redex-generator* is a new, experimental form, and its API may change.

Returns a thunk that, each time it is called, either generates a random s-expression based on *satisfying* or fails to (and returns #f). The terms returned by a particular thunk are guaranteed to be distinct.

Examples:

```

> (define-language L
   (nat ::= Z (S nat)))

> (define-judgment-form L
   #:mode (sum I I 0)
   [-----
    (sum Z nat nat)]
   [(sum nat_1 nat_2 nat_3)
    -----
    (sum (S nat_1) nat_2 (S nat_3))])

> (define gen-sum (redex-generator L (sum nat_1 nat_2 nat_3) 3))

> (for/list ([_ (in-range 5)])
   (gen-sum))

```

```

'((sum Z (S Z) (S Z))
  (sum (S (S (S Z))) (S Z) (S (S (S (S Z))))))
  (sum (S (S (S (S Z)))) (S (S Z)) (S (S (S (S (S (S Z)))))))
  (sum (S (S Z)) Z (S (S Z)))
  (sum (S Z) (S (S Z)) (S (S (S Z)))))
(struct counterexample (term)
  #:extra-constructor-name make-counterexample
  #:transparent)
term : any/c

```

Produced by `redex-check`, `check-reduction-relation`, and `check-metafunction` when testing falsifies a property.

```

(struct exn:fail:redex:test exn:fail:redex (source term)
  #:extra-constructor-name make-exn:fail:redex:test)
source : exn:fail?
term : any/c

```

Raised by `redex-check`, `check-reduction-relation`, and `check-metafunction` when testing a property raises an exception. The `exn:fail:redex:test-source` component contains the exception raised by the property, and the `exn:fail:redex:test-term` component contains the term that induced the exception.

```

(check-reduction-relation relation property kw-args ...)

kw-arg = #:attempts attempts-expr
         | #:retries retries-expr
         | #:print? print?-expr
         | #:attempt-size attempt-size-expr
         | #:prepare prepare-expr

property : (-> any/c any/c)
attempts-expr : natural-number/c
retries-expr : natural-number/c
print?-expr : any/c
attempt-size-expr : (-> natural-number/c natural-number/c)
prepare-expr : (-> any/c any/c)

```

Tests `relation` as follows: for each case of `relation`, `check-reduction-relation` generates `attempts` random terms that match that case's left-hand side and applies `property` to each random term.

This form provides a more convenient notation for

```
(redex-check L any (property (term any))
 #:attempts (* n attempts)
 #:source relation)
```

when *relation* is a relation on L with n rules.

```
(check-metafunction metafunction property kw-args ...)

kw-arg = #:attempts attempts-expr
        | #:retries retries-expr
        | #:print? print?-expr
        | #:attempt-size attempt-size-expr
        | #:prepare prepare-expr

property : (-> (listof any/c) any/c)
attempts-expr : natural-number/c
retries-expr : natural-number/c
print?-expr : any/c
attempt-size-expr : (-> natural-number/c natural-number/c)
prepare-expr : (-> (listof any/c) (listof any/c))
```

Like `check-reduction-relation` but for metafunctions. `check-metafunction` calls *property* with lists containing arguments to the metafunction. Similarly, *prepare-expr* produces and consumes argument lists.

Examples:

```
> (define-language empty-lang)

> (define-metafunction empty-lang
  Σ : number ... -> number
  [(Σ) 0]
  [(Σ number) number]
  [(Σ number_1 number_2) ,(+ (term number_1) (term number_2))]
  [(Σ number_1 number_2 ...) (Σ number_1 (Σ number_2 ...))])

> (check-metafunction Σ (λ (args)
  (printf "trying ~s\n" args)
  (equal? (apply + args)
  (term (Σ ,@args))))
 #:attempts 2)

trying ()
trying ()
trying (0)
```

```

trying (0)
trying (2 1)
trying (0 1)
trying (0)
trying (1)
check-metafunction: no counterexamples in 2 attempts (with each
clause)

```

```

(default-attempt-size n) → natural-number/c
n : natural-number/c

```

The default value of the `#:attempt-size` argument to `redex-check` and the other randomized testing forms, this procedure computes an upper bound on the size of the next test case from the number of previously attempted tests `n`. Currently, this procedure computes the base 5 logarithm, but that behavior may change in future versions.

```

(default-check-attempts) → natural-number/c
(default-check-attempts attempts) → void?
attempts : natural-number/c

```

Determines the default value for `redex-check`'s optional `#:attempts` argument. By default, `attempts` is 1,000.

```

(redex-pseudo-random-generator) → pseudo-random-generator?
(redex-pseudo-random-generator generator) → void?
generator : pseudo-random-generator?

```

`generate-term` and the randomized testing forms (e.g., `redex-check`) use the parameter `generator` to construct random terms. The parameter's initial value is (`current-pseudo-random-generator`).

```

(exn:fail:redex:generation-failure? v) → boolean?
v : any/c

```

Recognizes the exceptions raised by `generate-term`, `redex-check`, etc. when those forms are unable to produce a term matching some pattern.

### *Debugging PLT Redex Programs*

It is easy to write grammars and reduction rules that are subtly wrong. Typically such mistakes result in examples that get stuck when viewed in a `traces` window.

The best way to debug such programs is to find an expression that looks like it should reduce, but doesn't, then try to find out which pattern is failing to match. To do so, use the `redex-match` form.

In particular, first check if the term in question matches the your system's main non-terminal (typically the expression or program non-terminal). If it does not match, simplify the term piece by piece to determine whether the problem is in the term or the grammar.

If the term does match your system's main non-terminal, determine by inspection which reduction rules should apply. For each such rule, repeat the above term-pattern debugging procedure, this time using the rule's left-hand side pattern instead of the system's main non-terminal. In addition to simplifying the term, also consider simplifying the pattern.

If the term matches the left-hand side, but the rule does not apply, then one of the rule's `side-condition` or `where` clauses is not satisfied. Using the bindings reported by `redex-match`, check each `side-condition` expression and each `where` pattern-match to discover which clause is preventing the rule's application.

## 2.7 GUI

```
(require redex/gui)      package: redex-gui-lib
```

This section describes the GUI tools that Redex provides for exploring reduction sequences.

```
(traces reductions
  expr
  [#:multiple? multiple?
   #:reduce reduce
   #:pred pred
   #:pp pp
   #:colors colors
   #:racket-colors? racket-colors?
   #:scheme-colors? scheme-colors?
   #:filter term-filter
   #:x-spacing x-spacing
   #:y-spacing y-spacing
   #:layout layout
   #:edge-labels? edge-labels?
   #:edge-label-font edge-label-font
   #:graph-pasteboard-mixin graph-pasteboard-mixin])
→ void?
reductions : reduction-relation?
expr : (or/c any/c (listof any/c))
multiple? : boolean? = #f
reduce : (-> reduction-relation? any/c
          (listof (list/c (union false/c string?) any/c)))
          = apply-reduction-relation/tag-with-names
pred : (or/c (-> sexp any)
          (-> sexp term-node? any)) = (λ (x) #t)
```



```

pp : (or/c (any -> string)
          (any output-port number (is-a?/c text%) -> void))
    = default-pretty-printer
      (listof
        (cons/c string?
          (and/c (listof (or/c string? (is-a?/c color%)))
                 (λ (x) (<= 0 (length x) 6))))))
    = '()
racket-colors? : boolean? = #t
scheme-colors? : boolean? = racket-colors?
term-filter : (-> any/c (or/c #f string?) any/c)
             = (λ (x y) #t)
x-spacing : number? = 15
y-spacing : number? = 15
layout : (-> (listof term-node?) void?) = void
edge-labels? : boolean? = #t
edge-label-font : (or/c #f (is-a?/c font%)) = #f
graph-pasteboard-mixin : (make-mixin-contract graph-pasteboard<%>)
                       = values

```

This function opens a new window and inserts each expression in *expr* (if *multiple?* is *#t* – if *multiple?* is *#f*, then *expr* is treated as a single expression). Then, it reduces the terms until at least *reduction-steps-cutoff* (see below) different terms are found, or no more reductions can occur. It inserts each new term into the gui. Clicking the reduce button reduces until *reduction-steps-cutoff* more terms are found.

The *reduce* function applies the reduction relation to the terms. By default, it is *apply-reduction-relation/tag-with-names*; it may be changed to only return a subset of the possible reductions, for example, but it must satisfy the same contract as *apply-reduction-relation/tag-with-names*.

The *pred* function indicates if a term has a particular property. If it returns *#f*, the term is displayed with a pink background. If it returns a string or a *color%* object, the term is displayed with a background of that color (using *the-color-database* to map the string to a color). If it returns any other value, the term is displayed normally. If the *pred* function accepts two arguments, a term-node corresponding to the term is passed to the predicate. This lets the predicate function explore the (names of the) reductions that led to this term, using *term-node-children*, *term-node-parents*, and *term-node-labels*.

The *pred* function may be called more than once per node. In particular, it is called each time an edge is added to a node. The latest value returned determines the color.

The *pp* function is used to specially print expressions. It must either accept one or four arguments. If it accepts one argument, it will be passed each term and is expected to return a string to display the term.

If the `pp` function takes four arguments, it should render its first argument into the port (its second argument) with width at most given by the number (its third argument). The final argument is the text where the port is connected – characters written to the port go to the end of the editor. Use `write-special` to send `snip%` objects or `2htdp/image` images (or other things that subscribe to `file/convertible` or `pict/convert`) directly to the editor.

The `colors` argument, if provided, specifies a list of reduction-name/color-list pairs. The `traces` gui will color arrows drawn because of the given reduction name with the given color instead of using the default color.

The `cdr` of each of the elements of `colors` is a list of colors, organized in pairs. The first two colors cover the colors of the line and the border around the arrow head, the first when the mouse is over a graph node that is connected to that arrow, and the second for when the mouse is not over that arrow. Similarly, the next colors are for the text drawn on the arrow and the last two are for the color that fills the arrow head. If fewer than six colors are specified, the specified colors are used and then defaults are filled in for the remaining colors.

The `racket-colors?` argument (along with `scheme-colors?`, retained for backward compatibility), controls the coloring of each window. When `racket-colors?` is `#t` (and `scheme-colors?` is `#t` too), `traces` colors the contents according to DrRacket’s Racket-mode color scheme; otherwise, `traces` uses a black color scheme.

The `term-filter` function is called each time a new node is about to be inserted into the graph. If the filter returns false, the node is not inserted into the graph.

The `x-spacing` and `y-spacing` control the amount of space put between the snips in the default layout.

The `layout` argument is called (with all of the terms) when new terms are inserted into the window. In general, it is called after new terms are inserted in response to the user clicking on the reduce button, and after the initial set of terms is inserted. See also `term-node-set-position!`.

If `edge-labels?` is `#t` (the default), then edge labels are drawn; otherwise not.

The `edge-label-font` argument is used as the font on the edge labels. If `#f` is supplied, the `dc<%>` object’s default font is used.

The `traces` library uses an instance of the `mrlib/graph` library’s `graph-pasteboard<%>` interface to layout the graphs. Sometimes, overriding one of its methods can help give finer-grained control over the layout, so the `graph-pasteboard-mixin` is applied to the class before it is instantiated. Also note that all of the snips inserted into the editor by this library have a `get-term-node` method which returns the snip’s `term-node`.

For a more serious example of `traces`, please see §1 “Amb: A Redex Tutorial”, but for a silly one that demonstrates how the `pp` argument lets us use images, we can take the pairing

functions discussed in Matthew Szudzik's *An Elegant Pairing Function* presentation:

```
(define/contract (unpair z)
  (-> exact-nonnegative-integer?
    (list/c exact-nonnegative-integer? exact-nonnegative-integer?))
  (define i (integer-sqrt z))
  (define i2 (* i i))
  (cond
    [(< (- z i2) i)
     (list (- z i2) i)]
    [else
     (list i (- z i2 i))]))

(define/contract (pair x y)
  (-> exact-nonnegative-integer? exact-nonnegative-integer?
    exact-nonnegative-integer?)
  (if (= x (max x y))
      (+ (* x x) x y)
      (+ (* y y) x)))
```

and build a reduction relation out of them:

```
(define-language L (n ::= natural))
(define red
  (reduction-relation
    L
    (--> (n_1 n_2)
      ,(unpair (+ 1 (pair (term n_1)
                          (term n_2)))))))
(traces red (term (0 0)))
```

We can then turn those two numbers into two stars, where the number indicates the number of points in the star:

```
(require 2htdp/image)
(define/contract (two-stars point-count1 point-count2)
  (-> (>=/c 2) (>=/c 2) image?)
  (overlay
    (radial-star (+ 2 point-count1)
      10 60
      "solid"
      (make-color 255 0 255 150)))
```

```
(radial-star (+ 2 point-count2)
             10 60
             "solid"
             "cornflowerblue"))
```

and then use the `pp` function to show those in the traces window instead of just the numbers.

```
(traces red
 (term (0 0))
 #:pp
 (λ (term port w txt)
  (write-special
   (two-stars (+ 2 (list-ref term 0))
              (+ 2 (list-ref term 1)))
   port)))

(traces/ps reductions
 expr
 file
 [#:multiple? multiple?
 #:reduce reduce
 #:pred pred
 #:pp pp
 #:colors colors
 #:filter term-filter
 #:layout layout
 #:x-spacing x-spacing
 #:y-spacing y-spacing
 #:edge-labels? edge-labels?
 #:edge-label-font edge-label-font
 #:graph-pasteboard-mixin graph-pasteboard-mixin]
 #:post-process post-process)
→ void?
reductions : reduction-relation?
expr : (or/c any/c (listof any/c))
file : (or/c path-string? path?)
multiple? : boolean? = #f
reduce : (-> reduction-relation? any/c
          (listof (list/c (union false/c string?) any/c)))
          = apply-reduction-relation/tag-with-names
pred : (or/c (-> sexp any)
          (-> sexp term-node? any)) = (λ (x) #t)
pp : (or/c (any -> string)
          (any output-port number (is-a?/c text%) -> void))
      = default-pretty-printer
```

```

      (listof
colors : (cons/c string?
          (and/c (listof (or/c string? (is-a?/c color%)))
                  (λ (x) (<= 0 (length x) 6))))))
      = '()
term-filter : (-> any/c (or/c #f string?) any/c)
             = (λ (x y) #t)
layout : (-> (listof term-node?) void?) = void
x-spacing : number? = 15
y-spacing : number? = 15
edge-labels? : boolean? = #t
edge-label-font : (or/c #f (is-a?/c font%)) = #f
graph-pasteboard-mixin : (make-mixin-contract graph-pasteboard<*>)
                        = values
post-process : (-> (is-a?/c graph-pasteboard<*>) any/c)

```

This function behaves just like the function `traces`, but instead of opening a window to show the reduction graph, it just saves the reduction graph to the specified *file*.

All of the arguments behave like the arguments to `traces`, with the exception of the *post-process* argument. It is called just before the PostScript is created with the graph pasteboard.

```

(stepper reductions t [pp]) → void?
reductions : reduction-relation?
t : any/c
pp : (or/c (any -> string)
        (any output-port number (is-a?/c text%) -> void))
     = default-pretty-printer

```

This function opens a stepper window for exploring the behavior of the term *t* in the reduction system given by *reductions*.

The *pp* argument is the same as to the `traces` function but is here for backwards compatibility only and should not be changed for most uses, but instead adjusted with `pretty-print-parameters`. Specifically, the highlighting shown in the stepper window can be wrong if `default-pretty-printer` does not print sufficiently similarly to how `pretty-print` prints (when adjusted by `pretty-print-parameters`'s behavior, of course).

```

(stepper/seed reductions seed [pp]) → void?
reductions : reduction-relation?
seed : (cons/c any/c (listof any/c))
pp : (or/c (any -> string)
        (any output-port number (is-a?/c text%) -> void))
     = default-pretty-printer

```

Like `stepper`, this function opens a stepper window, but it seeds it with the reduction-sequence supplied in `seed`.

```
(show-derivations derivations
  [#:pp pp
   #:racket-colors? racket-colors?
   #:init-derivation init-derivation]) → any
derivations : (cons/c derivation? (listof derivation?))
pp : (or/c (any -> string)
         (any output-port number (is-a?/c text%) -> void))
      = default-pretty-printer
racket-colors? : boolean? = #f
init-derivation : exact-nonnegative-integer? = 0
```

Opens a window to show `derivations`.

The `pp` and `racket-colors?` arguments are like those to `traces`.

The initial derivation shown in the window is chosen by `init-derivation`, used as an index into `derivations`.

```
(derivation/ps derivation
  filename
  [#:pp pp
   #:racket-colors? racket-colors?]
  #:post-process post-process) → void?
derivation : derivation?
filename : path-string?
pp : (or/c (any -> string)
         (any output-port number (is-a?/c text%) -> void))
      = default-pretty-printer
racket-colors? : boolean? = #f
post-process : (-> (is-a?/c pasteboard%) any)
```

Like `show-derivations`, except it prints a single derivation in PostScript to `filename`.

```
(term-node-children tn) → (listof term-node?)
tn : term-node?
```

Returns a list of the children (ie, terms that this term reduces to) of the given node.

Note that this function does not return all terms that this term reduces to – only those that are currently in the graph.

```
(term-node-parents tn) → (listof term-node?)
tn : term-node?
```

Returns a list of the parents (ie, terms that reduced to the current term) of the given node.

Note that this function does not return all terms that reduce to this one – only those that are currently in the graph.

```
(term-node-labels tn) → (listof (or/c false/c string?))
tn : term-node?
```

Returns a list of the names of the reductions that led to the given node, in the same order as the result of `term-node-parents`. If the list contains `#f`, that means that the corresponding step does not have a label.

```
(term-node-set-color! tn color) → void?
tn : term-node?
color : (or/c string? (is-a?/c color%) false/c)
```

Changes the highlighting of the node; if its second argument is `#f`, the coloring is removed, otherwise the color is set to the specified `color%` object or the color named by the string. The `color-database<%>` is used to convert the string to a `color%` object.

```
(term-node-color tn) → (or/c string? (is-a?/c color%) false/c)
tn : term-node?
```

Returns the current highlighting of the node. See also `term-node-set-color!`.

```
(term-node-set-red! tn red?) → void?
tn : term-node?
red? : boolean?
```

Changes the highlighting of the node; if its second argument is `#t`, the term is colored pink, if it is `#f`, the term is not colored specially.

```
(term-node-expr tn) → any
tn : term-node?
```

Returns the expression in this node.

```
(term-node-set-position! tn x y) → void?
tn : term-node?
x : (and/c real? positive?)
y : (and/c real? positive?)
```

Sets the position of `tn` in the graph to  $(x,y)$ .

```
(term-node-x tn) → real?  
  tn : term-node?
```

Returns the x coordinate of *tn* in the window.

```
(term-node-y tn) → real?  
  tn : term-node?
```

Returns the y coordinate of *tn* in the window.

```
(term-node-width tn) → real?  
  tn : term-node?
```

Returns the width of *tn* in the window.

```
(term-node-height tn) → real?  
  tn : term-node?
```

Returns the height of *tn* in the window.

```
(term-node? v) → boolean?  
  v : any/c
```

Recognizes term nodes.

```
(reduction-steps-cutoff) → number?  
(reduction-steps-cutoff cutoff) → void?  
  cutoff : number?
```

A parameter that controls how many steps the `traces` function takes before stopping.

```
(initial-font-size) → number?  
(initial-font-size size) → void?  
  size : number?
```

A parameter that controls the initial font size for the terms shown in the GUI window.

```
(initial-char-width) → (or/c number? (-> any/c number?))  
(initial-char-width width) → void?  
  width : (or/c number? (-> any/c number?))
```



A parameter that determines the initial width of the boxes where terms are displayed (measured in characters) for both the stepper and traces.

If its value is a number, then the number is used as the width for every term. If its value is a function, then the function is called with each term and the resulting number is used as the width.

```
(dark-pen-color) → (or/c string? (is-a?/c color<%>))
(dark-pen-color color) → void?
  color : (or/c string? (is-a?/c color<%>))
(dark-brush-color) → (or/c string? (is-a?/c color<%>))
(dark-brush-color color) → void?
  color : (or/c string? (is-a?/c color<%>))
(light-pen-color) → (or/c string? (is-a?/c color<%>))
(light-pen-color color) → void?
  color : (or/c string? (is-a?/c color<%>))
(light-brush-color) → (or/c string? (is-a?/c color<%>))
(light-brush-color color) → void?
  color : (or/c string? (is-a?/c color<%>))
(dark-text-color) → (or/c string? (is-a?/c color<%>))
(dark-text-color color) → void?
  color : (or/c string? (is-a?/c color<%>))
(light-text-color) → (or/c string? (is-a?/c color<%>))
(light-text-color color) → void?
  color : (or/c string? (is-a?/c color<%>))
```

These six parameters control the color of the edges in the graph.

The dark colors are used when the mouse is over one of the nodes that is connected to this edge. The light colors are used when it isn't.

The pen colors control the color of the line. The brush colors control the color used to fill the arrowhead and the text colors control the color used to draw the label on the edge.

```
(pretty-print-parameters) → (-> (-> any/c) any/c)
(pretty-print-parameters f) → void?
  f : (-> (-> any/c) any/c)
```

A parameter that is used to set other `pretty-print` parameters.

Specifically, whenever `default-pretty-printer` prints something it calls `f` with a thunk that does the actual printing. Thus, `f` can adjust `pretty-print`'s parameters to adjust how printing happens.

```
(default-pretty-printer v port width text) → void?
  v : any/c
  port : output-port?
```

```
width : exact-nonnegative-integer?
text : (is-a?/c text%)
```

This is the default value of `pp` used by `traces` and `stepper` and it uses `pretty-print`.

This function uses the value of `pretty-print-parameters` to adjust how it prints.

It sets the `pretty-print-columns` parameter to `width`, and it sets `pretty-print-size-hook` and `pretty-print-print-hook` to print holes and the symbol `'hole` to match the way they are input in a term expression.

## 2.8 Typesetting

```
(require redex/pict) package: redex-pict-lib
```

The `redex/pict` library provides functions designed to automatically typeset grammars, reduction relations, and metafunction written with `plt redex`.

Each grammar, reduction relation, and metafunction can be saved in a `.ps` file (as encapsulated postscript), or can be turned into a `pict` for viewing in the REPL or using with Slideshow (see the `pict` library).

### 2.8.1 Picts, PDF, & PostScript

This section documents two classes of operations, one for direct use of creating postscript figures for use in papers and for use in DrRacket to easily adjust the typesetting: `render-term`, `render-language`, `render-reduction-relation`, `render-relation`, `render-judgment-form`, `render-metafunctions`, and `render-lw`, and one for use in combination with other libraries that operate on `picts` `term->pict`, `language->pict`, `reduction-relation->pict`, `relation->pict`, `judgment-form->pict`, `metafunction->pict`, and `lw->pict`. The primary difference between these functions is that the former list sets `dc-for-text-size` and the latter does not.

```
(render-term lang term)
(render-term lang term file)
```

Renders the term `term`. If `file` is `#f` or not present, `render-term` produces a `pict`; if `file` is a path, it saves Encapsulated PostScript in the provided filename, unless the filename ends with `".pdf"`, in which case it saves PDF.

The `term` argument must be a literal; it is not an evaluated position. For example, this:

```
(define-language L)
(define x (term (+ 1 2)))
(render-term L x)
```

will render the term `x`, not the term `(+ 1 2)`.

See [render-language](#) for more details on the construction of the pict.

```
(term->pict lang term)
```

Produces a pict like `render-term`, but without adjusting `dc-for-text-size`.

The first argument is expected to be a `compiled-language?` and the second argument is expected to be a term (without the `term` wrapper). The formatting in the `term` argument is used to determine how the resulting pict will look.

This function is primarily designed to be used with Slideshow or with other tools that combine `picts` together.

```
(render-term/pretty-write lang
                          term
                          filename
                          #:width width) → void?
lang : compiled-lang?
term  : any/c
filename : path-string?
width  : #f
```

Like `render-term`, except that the `term` argument is evaluated, and expected to return a term. Then, `pretty-write` is used to determine where the line breaks go, using the `width` argument as a maximum width (via `pretty-print-columns`).

```
(term->pict/pretty-write lang
                        term
                        filename
                        #:width width) → pict?
lang : compiled-lang?
term  : any/c
filename : (or/c path-string? #f)
width  : #f
```

Like `term->pict`, but with the same change that `render-term/pretty-write` has from `render-term`.

```
(render-language lang [file #:nts nts]) → (if file void? pict?)
```

```

lang : compiled-lang?
file : (or/c false/c path-string?) = #f
nts : (or/c false/c (listof (or/c string? symbol?)))
      = (render-language-nts)

```

Renders a language. If *file* is #f, it produces a pict; if *file* is a path, it saves Encapsulated PostScript in the provided filename, unless the filename ends with ".pdf", in which case it saves PDF. See [render-language-nts](#) for information on the *nts* argument.

This function parameterizes [dc-for-text-size](#) to install a relevant dc: a [bitmap-dc%](#) or a [post-script-dc%](#), depending on whether *file* is a path.

See [language->pict](#) if you are using Slideshow or are otherwise setting [dc-for-text-size](#).

```

(language->pict lang [#:nts nts]) → pict?
lang : compiled-lang?
nts : (or/c false/c (listof (or/c string? symbol?)))
      = (render-language-nts)

```

Produce a pict like [render-language](#), but without adjusting [dc-for-text-size](#).

This function is primarily designed to be used with Slideshow or with other tools that combine [picts](#) together.

```

(render-reduction-relation rel
                           [file
                            #:style style])
→ (if file void? pict?)
rel : reduction-relation?
file : (or/c false/c path-string?) = #f
style : reduction-rule-style/c = (rule-pict-style)

```

Renders a reduction relation. If *file* is #f, it produces a pict; if *file* is a path, it saves Encapsulated PostScript in the provided filename, unless the filename ends with ".pdf", in which case it saves PDF. See [rule-pict-style](#) for information on the *style* argument.

This function parameterizes [dc-for-text-size](#) to install a relevant dc: a [bitmap-dc%](#) or a [post-script-dc%](#), depending on whether *file* is a path. See also [reduction-relation->pict](#).

The following forms of arrows can be typeset:

```

-->  -+>  ==>  ->  =>  ..>  >->  ~~>  ~>  :->  :->  c->  ->>
>-   -<   >>-   -<<

```

```
(reduction-relation->pict r [#:style style]) → pict?
  r : reduction-relation?
  style : reduction-rule-style/c = (rule-pict-style)
```

Produces a pict like `render-reduction-relation`, but without setting `dc-for-text-size`.

This function is primarily designed to be used with Slideshow or with other tools that combine `picts` together.

```
(render-metafunction metafunction-name)
(render-metafunction metafunction-name filename)
(render-metafunctions metafunction-name ...)
(render-metafunctions metafunction-name ... #:file filename)
```

Like `render-reduction-relation` but for metafunctions.

Similarly, `render-metafunctions` accepts multiple metafunctions and renders them together, lining up all of the clauses together.

This function sets `dc-for-text-size`. See also `metafunction->pict` and `metafunctions->pict`.

```
(metafunction->pict metafunction-name)
```

This produces a pict, but without setting `dc-for-text-size`. It is suitable for use in Slideshow or other libraries that combine `picts`.

```
(metafunctions->pict metafunction-name ...)
```

Like `metafunction->pict`, this produces a `pict`, but without setting `dc-for-text-size` and is suitable for use in Slideshow or other libraries that combine `picts`. Like `render-metafunctions`, it accepts multiple metafunctions and renders them together.

```
(render-relation relation-name)
(render-relation relation-name filename)
```

Like `render-metafunction` but for relations.

This function sets `dc-for-text-size`. See also `relation->pict`.

```
(render-judgment-form judgment-form-name)
(render-judgment-form judgment-form-name filename)
```

Like `render-metafunction` but for judgment forms.

This function sets `dc-for-text-size`. See also `judgment-form->pict`.

```
(relation->pict relation-name)
```

This produces a pict, but without setting `dc-for-text-size`. It is suitable for use in Slideshow or other libraries that combine `picts`.

```
(judgment-form->pict judgment-form-name)
```

This produces a pict, but without setting `dc-for-text-size`. It is suitable for use in Slideshow or other libraries that combine `picts`.

## 2.8.2 Customization

```
(render-language-nts) → (or/c false/c (listof symbol?))  
(render-language-nts nts) → void?  
  nts : (or/c false/c (listof symbol?))
```

The value of this parameter controls which non-terminals `render-language` and `language->pict` render by default. If it is `#f` (the default), all non-terminals are rendered. If it is a list of symbols, only the listed symbols are rendered.

See also `language-nts`.

```
(extend-language-show-union) → boolean?  
(extend-language-show-union show?) → void?  
  show? : boolean?
```

If this is `#t`, then a language constructed with `extend-language` is shown as if the language had been constructed directly with `language`. If it is `#f`, then only the last extension to the language is shown (with four-period ellipses, just like in the concrete syntax).

Defaults to `#f`.

Note that the `#t` variant can look a little bit strange if `. . . .` are used and the original version of the language has multi-line right-hand sides.

```
(render-reduction-relation-rules)  
  (or/c false/c  
    → (listof (or/c symbol?  
                string?  
                exact-nonnegative-integer?)))
```

```
(render-reduction-relation-rules rules) → void?
  (or/c false/c
   rules : (listof (or/c symbol?
                    string?
                    exact-nonnegative-integer?)))
```

This parameter controls which rules in a reduction relation will be rendered. The strings and symbols match the names of the rules and the integers match the position of the rule in the original definition.

```
(rule-pict-style) → reduction-rule-style/c
(rule-pict-style style) → void?
  style : reduction-rule-style/c
```

This parameter controls the style used by default for the reduction relation. It can be `'horizontal`, where the left and right-hand sides of the reduction rule are beside each other or `'vertical`, where the left and right-hand sides of the reduction rule are above each other. The `'compact-vertical` style moves the reduction arrow to the second line and uses less space between lines. The `'vertical-overlapping-side-conditions` variant, the side-conditions don't contribute to the width of the pict, but are just overlaid on the second line of each rule. The `'horizontal-left-align` style is like the `'horizontal` style, but the left-hand sides of the rules are aligned on the left, instead of on the right. The `'horizontal-side-conditions-same-line` is like `'horizontal`, except that side-conditions are on the same lines as the rule, instead of on their own line below.

```
reduction-rule-style/c : flat-contract?
```

A contract equivalent to

```
(or/c 'vertical
      'compact-vertical
      'vertical-overlapping-side-conditions
      'horizontal
      'horizontal-left-align
      'horizontal-side-conditions-same-line)
```

```
(arrow-space) → natural-number/c
(arrow-space space) → void?
  space : natural-number/c
```

This parameter controls the amount of extra horizontal space around the reduction relation arrow. Defaults to 0.

```
(label-space) → natural-number/c
(label-space space) → void?
  space : natural-number/c
```

This parameter controls the amount of extra space before the label on each rule, except in the `'vertical` and `'vertical-overlapping-side-conditions` modes, where it has no effect. Defaults to 0.

```
(metafunction-pict-style)
  (or/c 'left-right
        'up-down
        'left-right/vertical-side-conditions
→      'up-down/vertical-side-conditions
        'left-right/compact-side-conditions
        'up-down/compact-side-conditions
        'left-right/beside-side-conditions)
(metafunction-pict-style style) → void?
  (or/c 'left-right
        'up-down
        'left-right/vertical-side-conditions
style : 'up-down/vertical-side-conditions
        'left-right/compact-side-conditions
        'up-down/compact-side-conditions
        'left-right/beside-side-conditions)
```

This parameter controls the style used for typesetting metafunctions. The `'left-right` style means that the results of calling the metafunction are displayed to the right of the arguments and the `'up-down` style means that the results are displayed below the arguments.

The `'left-right/vertical-side-conditions` and `'up-down/vertical-side-conditions` variants format side conditions each on a separate line, instead of all on the same line.

The `'left-right/compact-side-conditions` and `'up-down/compact-side-conditions` variants move side conditions to separate lines to avoid making the rendered form wider than it would be otherwise.

The `'left-right/beside-side-conditions` variant is like `'left-right`, except it puts the side-conditions on the same line, instead of on a new line below the case.

```
(delimit-ellipsis-arguments?) → any/c
(delimit-ellipsis-arguments? delimit?) → void?
delimit? : any/c
```

This parameter controls the typesetting of metafunction definitions and applications. When it is non-`#f` (the default), commas precede ellipses that represent argument sequences; when it is `#f` no commas appear in those positions.

```
(linebreaks) → (or/c #f (listof boolean?))
(linebreaks breaks) → void?
breaks : (or/c #f (listof boolean?))
```



This parameter controls which cases in the metafunction are rendered on two lines and which are rendered on one.

If its value is a list, the length of the list must match the number of cases and each boolean indicates if that case has a linebreak or not.

This influences the 'left/right styles only.

```
(metafunction-cases)
  (or/c #f (and/c (listof (or/c exact-nonnegative-integer?
                          string?))
                  pair?))
→
(metafunction-cases cases) → void?
  (or/c #f (and/c (listof (or/c exact-nonnegative-integer?
                          string?))
                  pair?))
cases :
```

Controls which cases in a metafunction are rendered. If it is #f (the default), then all of the cases appear. If it is a list, then only the selected cases appear. The numbers indicate the cases counting from 0 and the strings indicate cases named with clause-name.

This parameter also controls how which clauses in judgment forms are rendered, but only in the case that judgment-form-cases is #f (and in that case, only the numbers are used).

```
(judgment-form-cases)
  (or/c #f
    (and/c (listof (or/c exact-nonnegative-integer?
                  string?))
           pair?))
→
(judgment-form-cases cases) → void?
  (or/c #f
    (and/c (listof (or/c exact-nonnegative-integer?
                  string?))
           pair?))
cases :
```

Controls which clauses in a judgment form are rendered. If it is #f (the default), then all of them are rendered. If it is a list, then only the selected clauses appear (numbers count from 0, and strings correspond to the labels in a judgment form).

```
(label-style) → text-style/c
(label-style style) → void?
  style : text-style/c
(grammar-style) → text-style/c
(grammar-style style) → void?
  style : text-style/c
(paren-style) → text-style/c
(paren-style style) → void?
  style : text-style/c
```

```

(literal-style) → text-style/c
(literal-style style) → void?
  style : text-style/c
(metafunction-style) → text-style/c
(metafunction-style style) → void?
  style : text-style/c
(non-terminal-style) → text-style/c
(non-terminal-style style) → void?
  style : text-style/c
(non-terminal-subscript-style) → text-style/c
(non-terminal-subscript-style style) → void?
  style : text-style/c
(non-terminal-superscript-style) → text-style/c
(non-terminal-superscript-style style) → void?
  style : text-style/c
(default-style) → text-style/c
(default-style style) → void?
  style : text-style/c

```

These parameters determine the font used for various text in the pict. See [text](#) in the `texpict` collection for documentation explaining `text-style/c`. One of the more useful things it can be is one of the symbols `'roman`, `'swiss`, or `'modern`, which are a serif, sans-serif, and monospaced font, respectively. (It can also encode style information, too.)

The `label-style` is used for the reduction rule label names. The `literal-style` is used for names that aren't non-terminals that appear in patterns. The `metafunction-style` is used for the names of metafunctions. The `paren-style` is used for the parentheses (including “[”, “]”, “{”, and “}”, as well as “(” and “)”), but not for the square brackets used for in-hole decompositions, which use the `default-style`. The `grammar-style` is used for the “:=” and “|” in grammars.

The `non-terminal-style` parameter is used for the names of non-terminals. Two parameters style the text in the (optional) "underscore" component of a non-terminal reference. The first, `non-terminal-subscript-style`, applies to the segment between the underscore and the first caret (^) to follow it; the second, `non-terminal-superscript-style`, applies to the segment following that caret. For example, in the non-terminal reference `xyz`, `x` has style `non-terminal-style`, `y` has style `non-terminal-subscript-style`, and `z` has style `non-terminal-superscript-style`.

The `default-style` is used for parenthesis, the dot in dotted lists, spaces, the "where" and "fresh" in side-conditions, and other places where the other parameters aren't used.

```

(label-font-size) → (and/c (between/c 1 255) integer?)
(label-font-size size) → void?
  size : (and/c (between/c 1 255) integer?)

```

```

(metafunction-font-size) → (and/c (between/c 1 255)
                               integer?)
(metafunction-font-size size) → void?
  size : (and/c (between/c 1 255)
              integer?)
(default-font-size) → (and/c (between/c 1 255) integer?)
(default-font-size size) → void?
  size : (and/c (between/c 1 255) integer?)

```

These parameters control the various font sizes. The `default-font-size` is used for all of the font sizes except labels and metafunctions.

```

(reduction-relation-rule-separation)
→ (parameter/c (and/c integer? positive? exact?))
(reduction-relation-rule-separation sep) → void?
  sep : (parameter/c (and/c integer? positive? exact?))

```

Controls the amount of space between clauses in a reduction relation. Defaults to 4.

```

(curly-quotes-for-strings) → boolean?
(curly-quotes-for-strings on?) → void?
  on? : boolean?

```

Controls if the open and close quotes for strings are turned into “ and ” or are left as merely “ ”.

Defaults to `#t`.

```

(current-text) → (-> string? text-style/c number? pict?)
(current-text proc) → void?
  proc : (-> string? text-style/c number? pict?)

```

This parameter’s function is called whenever Redex typesets some part of a grammar, reduction relation, or metafunction. It defaults to the `pict` library’s `text` function.

```

(arrow->pict arrow) → pict?
  arrow : symbol?

```

Returns the `pict` corresponding to `arrow`.

```

(set-arrow-pict! arrow proc) → void?
  arrow : symbol?
  proc : (-> pict?)

```

This functions sets the `pict` for a given reduction-relation symbol. When typesetting a reduction relation that uses the symbol, the `thunk` will be invoked to get a `pict` to render it. The `thunk` may be invoked multiple times when rendering a single reduction relation.

```
(white-bracket-sizing)
  → (-> string? number? (values number? number? number? number?))
(white-bracket-sizing proc) → void?
  proc : (-> string? number? (values number? number? number? number?))
```

This parameter is used when typesetting metafunctions to determine how to create the `⌈` characters. Rather than using those characters directly (since glyphs tend not to be available in PostScript fonts), they are created by combining two `[` characters or two `]` characters together.

The procedure accepts a string that is either `"["` or `"]"`, and returns four numbers. The first two numbers determine the offset (from the left and from the right respectively) for the second square bracket, and the second two two numbers determine the extra space added (to the left and to the right respectively).

The default value of the parameter is:

```
(λ (str size)
  (let ([inset-amt (floor/even (max 4 (* size 1/2)))]))
  (cond
    [(equal? str "[")
     (values inset-amt
             0
             0
             (/ inset-amt 2))]
    [else
     (values 0
            inset-amt
            (/ inset-amt 2)
            0))]))
```

where `floor/even` returns the nearest even number below its argument. This means that for sizes 9, 10, and 11, `inset-amt` will be 4, and for 12, 13, 14, and 15, `inset-amt` will be 6.

```
(horizontal-bar-spacing)
  → (parameter/c exact-nonnegative-integer?)
(horizontal-bar-spacing space) → void?
  space : (parameter/c exact-nonnegative-integer?)
```

Controls the amount of space around the horizontal bar when rendering a relation (that was created by `define-relation`). Defaults to 4.

```
(relation-clauses-combine)
→ (parameter/c (-> (listof pict?) pict?))
(relation-clauses-combine combine) → void?
  combine : (parameter/c (-> (listof pict?) pict?))
```

The `combine` function is called with the list of pict's that are obtained by rendering a relation; it should put them together into a single pict. It defaults to `(λ (l) (apply vc-append 20 l))`

```
(where-make-prefix-pict) → (parameter/c (-> pict?))
(where-make-prefix-pict make-prefix) → void?
  make-prefix : (parameter/c (-> pict?))
```

The `make-prefix` function is called with no arguments to generate a pict that prefixes `where` clauses. It defaults to a function that produces a pict for “where” surrounded by spaces using the default style.

```
(where-combine) → (parameter/c (-> pict? pict? pict?))
(where-combine combine) → void?
  combine : (parameter/c (-> pict? pict? pict?))
```

The `combine` function is called with pict's for the left and right side of a `where` clause, and it should put them together into a single pict. It defaults to `(λ (l r) (hbl-append 1 =-pict r))`, where `=-pict` is an equal sign surrounded by spaces using the default style.

### 2.8.3 Removing the Pink Background

When reduction rules, a metafunction, or a grammar contains unquoted Racket code or side-conditions, they are rendered with a pink background as a guide to help find them and provide an alternative typesetting for them. In general, a good goal for a PLT Redex program that you intend to typeset is to only include such things when they correspond to standard mathematical operations, and the Racket code is an implementation of those operations.

To replace the pink code, use:

```
(with-unquote-rewriter proc expression)
```

Installs `proc` as the current unquote rewriter and evaluates `expression`. If that expression computes any pict's, the unquote rewriter specified is used to remap them.

The `proc` must match the contract `(-> lw? lw?)`. Its result should be the rewritten version of the input.

```
(with-atomic-rewriter name-symbol
                     string-or-thunk-returning-pict
                     expression)
```

This extends the current set of atomic-rewriters with one new one that rewrites the value of *name-symbol* to *string-or-pict-returning-thunk* (applied, in the case of a *thunk*), during the evaluation of *expression*.

*name-symbol* is expected to evaluate to a symbol. The value of *string-or-thunk-returning-pict* is used whenever the symbol appears in a pattern.

```
(with-compound-rewriter name-symbol
                       proc
                       expression)
```

This extends the current set of compound-rewriters with one new one that rewrites the value of *name-symbol* via *proc*, during the evaluation of *expression*.

*name-symbol* is expected to evaluate to a symbol. The value of *proc* is called with a `(listof lw)`, and is expected to return a new `(listof (or/c lw? string? pict?))`, rewritten appropriately.

The list passed to the rewriter corresponds to the *lw* for the sequence that has *name-symbol*'s value at its head.

The result list is constrained to have at most 2 adjacent non-*lws*. That list is then transformed by adding *lw* structs for each of the non-*lws* in the list (see the text just below the description of *lw* for an explanation of logical space):

- If there are two adjacent *lws*, then the logical space between them is filled with whitespace.
- If there is a pair of *lws* with just a single non-*lw* between them, a *lw* will be created (containing the non-*lw*) that uses all of the available logical space between the *lws*.
- If there are two adjacent non-*lws* between two *lws*, the first non-*lw* is rendered right after the first *lw* with a logical space of zero, and the second is rendered right before the last *lw* also with a logical space of zero, and the logical space between the two *lws* is absorbed by a new *lw* that renders using no actual space in the typeset version.

One useful way to take advantage of `with-compound-rewriters` is to return a list that begins and ends with "" (the empty string). In that situation, any extra logical space that would have been just outside the sequence is replaced with an *lw* that does not draw anything at all.

```
(with-compound-rewriters ([name-symbol proc] ...)
  expression)
```

Shorthand for nested with-compound-rewriter expressions.

#### 2.8.4 LWs

```
(struct lw (e
  line
  line-span
  column
  column-span
  unq?
  metafunction?)
  #:extra-constructor-name make-lw
  #:mutable)
(or/c string?
  symbol?
  pict?
  (listof (or/c (symbols 'spring) lw?)))
e :
  pict?
  (listof (or/c (symbols 'spring) lw?)))
line : exact-positive-integer?
line-span : exact-positive-integer?
column : exact-positive-integer?
column-span : exact-positive-integer?
unq? : boolean?
metafunction? : boolean?
```

The `lw` data structure corresponds represents a pattern or a Racket expression that is to be typeset. The functions listed above construct `lw` structs, select fields out of them, and recognize them. The `lw` binding can be used with `copy-struct`.

The values of the `unq?` and `metafunction?` fields, respectively, indicate whether the `lw` represents an unquoted expression or a metafunction application. See `to-lw` for the meanings of the other fields.

```
(build-lw e line line-span column column-span) → lw?
(or/c string?
  symbol?
  pict?
  (listof (or/c (symbols 'spring) lw?)))
line : exact-positive-integer?
line-span : exact-positive-integer?
column : exact-positive-integer?
column-span : exact-positive-integer?
```

Like `make-lw` but specialized for constructing `lws` that do not represent unquoted expressions or metafunction applications.

```
(to-lw arg)
```

This form turns its argument into `lw` structs that contain all of the spacing information just as it would appear when being used to typeset.

Each sub-expression corresponds to its own `lw`, and the element indicates what kind of subexpression it is. If the element is a list, then the `lw` corresponds to a parenthesized sequence, and the list contains a `lw` for the open paren, one `lw` for each component of the sequence and then a `lw` for the close parenthesis. In the case of a dotted list, there will also be a `lw` in the third-to-last position for the dot.

For example, this expression:

```
(a)
```

becomes this `lw` (assuming the above expression appears as the first thing in the file):

```
(build-lw (list (build-lw "(" 0 0 0 1)
                (build-lw 'a 0 0 1 1)
                (build-lw ")" 0 0 2 1))
          0 0 0 3)
```

If there is some whitespace in the sequence, like this one:

```
(a b)
```

then there is no `lw` that corresponds to that whitespace; instead there is a logical gap between the `lws`.

```
(build-lw (list (build-lw "(" 0 0 0 1)
                (build-lw 'a 0 0 1 1)
                (build-lw 'b 0 0 3 1)
                (build-lw ")" 0 0 4 1))
          0 0 0 5)
```

In general, identifiers are represented with symbols and parenthesis are represented with strings and `picts` can be inserted to render arbitrary pictures.

The line, line-span, column, and column-span correspond to the logical spacing for the redex program, not the actual spacing that will be used when they are rendered. The logical spacing is only used when determining where to place typeset portions of the program. In the absence



of any rewriters, these numbers correspond to the line and column numbers in the original program.

The line and column are absolute numbers from the beginning of the file containing the expression. The column number is not necessarily the column of the open parenthesis in a sequence – it is the leftmost column that is occupied by anything in the sequence. The line-span is the number of lines, and the column span is the number of columns on the last line (not the total width).

When there are multiple lines, lines are aligned based on the logical space (ie, the line/column & line-span/column-span) fields of the lws. As an example, if this is the original pattern:

```
(all good boys
  deserve fudge)
```

then the leftmost edges of the words "good" and "deserve" will be lined up underneath each other, but the relative positions of "boys" and "fudge" will be determined by the natural size of the words as they rendered in the appropriate font.

When 'spring appears in the list in the e field of a lw struct, then it absorbs all of the space around it. It is also used by to-lw when constructing the picts for unquoted strings. For example, this expression

```
,x
```

corresponds to these structs:

```
(build-lw (list (build-lw "" 1 0 9 0)
                'spring
                (build-lw x 1 0 10 1))
          1 0 9 2)
```

and the 'spring causes there to be no space between the empty string and the x in the typeset output.

```
(to-lw/stx stx) → lw?
  stx : syntax?
```

This is the runtime variant on to-lw; it accepts a syntax object and returns the corresponding lw structs. It only uses the location information in the syntax object, so metafunctions will not be rendered properly.

```
(render-lw language/nts lw) → pict?
  language/nts : (or/c (listof symbol?) compiled-lang?)
  lw : lw?
```

Produces a pict that corresponds to the `lw` object argument, using `language/nts` to determine which of the identifiers in the `lw` argument are non-terminals.

This function sets `dc-for-text-size`. See also `lw->pict`.

```
(lw->pict language/ntw lw) → pict?  
  language/ntw : (or/c (listof symbol?) compiled-lang?)  
  lw : lw?
```

Produces a pict that corresponds to the `lw` object argument, using `language/nts` to determine which of the identifiers in the `lw` argument are non-terminals.

This does not set the `dc-for-text-size` parameter. See also `render-lw`.

```
(just-before stuff lw) → lw?  
  stuff : (or/c pict? string? symbol?)  
  lw : lw?  
(just-after stuff lw) → lw?  
  stuff : (or/c pict? string? symbol?)  
  lw : lw?
```

These two helper functions build new lws whose contents are the first argument, and whose line and column are based on the second argument, making the new loc wrapper be either just before or just after that argument. The line-span and column-span of the new lw is always zero.

## 2.9 Macros and Typesetting

When you have a macro that abstracts over variations in Redex programs, then typesetting is unlikely to work without some help from your macros.

To see the issue, consider this macro abstraction over a Redex grammar:

```
> (define-syntax-rule  
  (def-my-lang L prim ...)  
  (define-language L  
    (e ::=  
      (λ (x) e)  
      (e e)  
      prim ...  
      x)  
    (x ::= variable-not-otherwise-mentioned)))  
  
> (def-my-lang L + - *)
```

```

> (render-language L)
eject: lines going backwards (current-line 3 line 2 atom
#<pict> tokens (#(struct:string-token 0 1 "*" swiss)
#(struct:pict-token 1 0 #<pict>) #(struct:string-token 0 1
"- " swiss) #(struct:pict-token 1 0 #<pict>)
#(struct:string-token 0 1 "+" swiss) #(struct:pict-token 0 0
#<pict>) #(struct:spacer-token 0 0)))

```

Redex thinks that the grammar is going “backwards” because of the way macro expansion synthesizes source locations. In particular, in the result of the macro expansion, the third production for `e` appears to come later in the file than the fourth production and this confuses Redex, making it unable to typeset this language.

One simple, not-very-general work-around is to just avoid typesetting the parts that come from the macro arguments. For example if you move the primitives into their own non-terminal and then just avoid typesetting that, Redex can cope:

```

(define-syntax-rule
  (def-my-lang L prim ...)
  (define-language L
    (e ::=
      (λ (x) e)
      (e e)
      prims
      x)
    (prims ::= prim ...)
    (x ::= variable-not-otherwise-mentioned)))

> (def-my-lang L + - *)

> (render-language L #:nts '(e x))
e ::= (λ (x) e)
      | (e e)
      | prims
      | x
x ::= variable-not-otherwise-mentioned

```

You can also, however, exploit Racket’s macro system to rewrite the source locations in a way that tells Redex where the macro-introduced parts of the language are supposed to be, and then typesetting will work normally. For example, here is one way to do this with the original language:

```

(define-syntax (def-my-lang stx)
  (syntax-case stx ()

```

```

[(_ L a ...)
 (let ()
  (define template
   #'(define-language L
      (e (λ (x) e)
        (e e)
        HERE
        x)
      (x variable-not-otherwise-mentioned)))
  (car
   (let loop ([stx template])
    (syntax-case stx (HERE)
     [HERE
      (let loop ([as (syntax->list #'(a ...))]
                 [pos (syntax-position stx)]
                 [col (syntax-column stx)])
       (cond
        [(null? as) '()]
        [else
         (define a (car as))
         (define span
          (string-length
           (symbol->string (syntax-e a))))
         (define srcloc
          (vector (syntax-source stx)
                  (syntax-line stx)
                  col
                  pos
                  span))
         (cons
          (datum->syntax a
                        (syntax-e a)
                        srcloc
                        a)
          (loop (cdr as)
                (+ pos span 1)
                (+ col span 1)))))]))
    [(a ...)
     (list
      (datum->syntax
       stx
       (apply append (map loop (syntax->list #'(a ...))))
       stx
       stx))]
    [a
     (list stx)])))]))

```

```
> (def-my-lang L + - *)
```

```
> (render-language L)
```

```
 $e ::= (\lambda (x) e)$ 
```

```
      |  $(e e)$ 
```

```
      | + | - | *
```

```
      |  $x$ 
```

```
 $x ::= \textit{variable-not-otherwise-mentioned}$ 
```

And one final caveat: when Racket compiles source files to bytecode format, it discards source location information in syntax constants, which means that if a file containing a macro like the one above is compiled to bytecode, then it cannot properly adjust the source locations and the typeset language will not look right (the important constant whose source locations are lost is `template`, above).

The simplest way to avoid this problem is to just avoid creating bytecode for these files.

It is possible to write the constant in the source code, however, and then process it so the compiled version of the file contains different data structures that record the source locations of the expressions. Redex does this internally so that compiled files that use, e.g., `define-language`, still correctly typeset. But when you write macros that expand into `define-language`, you must also take this step yourself (or avoid `.zo` files).

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