Titanium Language Reference Manual

Version 1.5, 9 November 2001

P. N. Hilfinger (editor), Dan Bonachea, David Gay,
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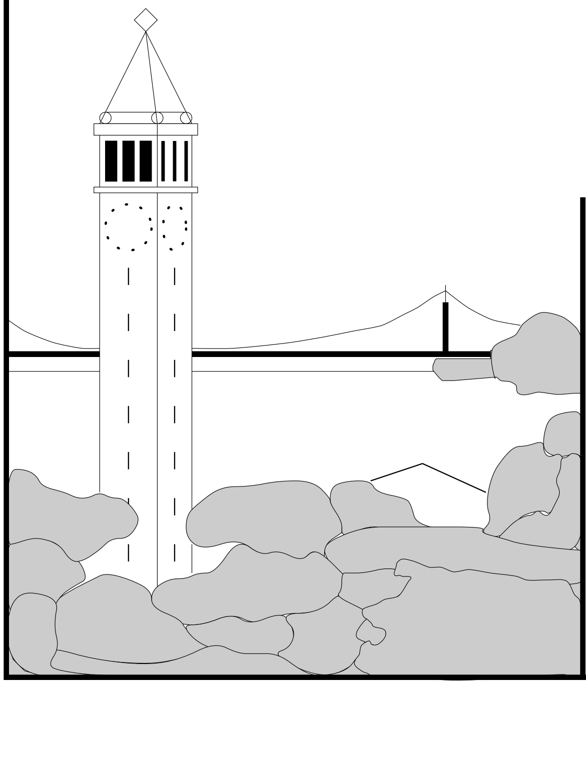

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Contents

Preface

This document informally describes our current design for the Titanium language. It is in the form of a set of changes to Java. Unless otherwise indicated, the reader may assume the syntax and semantics of Java, version 1.0.

Acknowledgments. Many people have contributed to the Titanium project over the years, both as implementors and commentators. We especially wish to thank Peter McCorquodale and Phillip Colella (of the Lawrence Berkeley National Laboratory) for their many comments. Former members of the Titanium group who have contributed to this report include Alexander Aiken, Andrew Begel, Joe Darcy, and Luigi Semenzato.

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Chapter 1

Lexical Structure

Titanium adds the following new keywords to Java:

`broadcast`	`foreach`	`from`	`immutable`	`inline`
`local`	`nonshared`	`op`	`overlap`	`partition`
`polyshared`	`sglobal`	`single`	`template`	

and the following reserved identifiers:

`Domain`	`Point`	`RectDomain`

Chapter 2

Program Structure

Types introduced by Titanium are contained in the package `ti.lang` ('Ti' being the standard chemical symbol for Titanium). There is an implicit declaration

```
import ti.lang.*;
```

at the beginning of each Titanium program.

The main procedure of a Titanium program must have signature

```
public single static void main(String single [] single args) {
  ...
}
```

However, this is sufficiently annoying that the standard Java declaration

```
public static void main(String [] args) {
  ...
}
```

is allowed as an abbreviation.

Chapter 3

New Standard Types and Constructors

3.1 Points

The immutable class Point<N>, for N a manifest positive integer constant, is a tuple of N int's. Point<N>s are used as indices into N-dimensional arrays.

Operations. In the following definitions, p and p_i are of type Point<N>; x, k, and k_i are integers;

- p[i], $1 \leq i \leq N$, is component i of p. That's right: the numbering starts at 1. It is an error for i to be out of bounds.
- [$k_1, \ldots, k_n$] is a point whose component i is k_i.
- Point<N>.all(x) is the Point<N> each of whose components is x.
- Point<N>.direction(d, x) for $1 \leq |d| \leq N$, is the Point<N> whose component $|d|$ is $x \cdot \mathrm{sign}(d)$, and whose other components are 0. x defaults to 1.
- The arithmetic operators +, -, *, /, applied to two Point<N>s produce Point<N>s by componentwise operations. * and / are also defined between Point<N>s and (scalar) integers: for p a Point<N>, s a scalar, and $\oplus$ an arithmetic operator, $p \oplus s =$ p $\oplus$ Point<N>.all(s) and $s \oplus p =$ Point<N>.all(s) $\oplus$ p. The / operator, in contrast to its meaning on two scalar integer operands, rounds toward $-\infty$, rather than toward 0. It is an error to divide by 0.
- If R is any of <, >, <=, >=, or ==, then p_0 R p_1 for Point<N>s p_0 and p_1, if p_0[i] R p_1[i] for all $1 \leq i \leq N$. The expression p_0!=p_1 is equivalent to !(p_0==p_1).

- The expression p_0`.permute (`p_1`)`, where the p_i are `Point<N>`s and p_1 is a permutation of $1, \ldots, N$ is the `Point<N>` p for which $p[p_1[i]] = p_0[i]$.
- p`.arity` $= N$, and is a manifest constant.
- The expression p`.toString()` yields a text representation of p.

3.2 Domains and RectDomains

The type `Domain<N>`, for N a manifest positive integer constant, is an arbitrary set of `Point<N>`s. The type `RectDomain<N>` is a "rectangular" set of `Point<N>`s: that is, a set

$$\{p \mid p_0 \leq p \leq p_1, \text{ and for some } x, \; p = p_0 + S{*}x\}$$

where all quantities here are `Point<N>`s. S here (a `Point<N>`) is called the *stride* of the `RectDomain<N>`, p_0 the *origin,* and p_1 the *upper bound.* `RectDomain<N>`s are used as the index sets (bounds) of N-dimensional arrays.

Operations: In the following descriptions, N is positive integer, D is a `Domain<N>`, R is a `RectDomain<N>`, and RD may be either a `Domain<N>` or a `RectDomain<N>`.

- There is a standard (implicit) coercion from `RectDomain<N>` to `Domain<N>`.
- RD`.isRectangular()` is true for all `RectDomain`s and for any `Domain` that is rectangular.
- A `Domain<N>` may be explicitly converted to a `RectDomain<N>` using the usual conversion syntax: `(RectDomain<N>)` D. It is a run-time error if D is not rectangular.

- If p_0 and p_1 are `Point<N>`s, then `[` p_0 : p_1 `]` is the `RectDomain<N>` with stride `Point<N>.all(1)`, origin p_0, and upper bound p_1. If s is also a `Point<N>`, $s >$ `Point<N>.all(0)`, then `[` $p_0 : p_1 : s$ `]` is the `RectDomain<N>` with origin p_0, upper bound p_1, and stride s. Because of the definitions of origin and upper bound at the beginning of this section, it follows that if not $p_0 \leq p_1$, then both `[` $p_0 : p_1$ `]` and `[` $p_0 : p_1 : s$ `]` are empty.

  So, for example, to get the set of all `Point<2>`s of the form $[i, j]$, with $0 \leq i < M$ and $0 \leq j < N$, we may use

  ```
  [ [0, 0] :  [M-1, N-1] ]
  ```

and to get the subset of this set in which all coordinates are even we may write

```
[ [0, 0] :  [M-1, N-1] :  [2, 2] ]
```

- If i_j, k_j, and s_j, $1 \leq j \leq N$, are `int`s, with $s_j > 0$, then

  `[` $i_1 : k_1 : s_1, \ldots, i_N : k_N : s_N$`]`

  is the same as

  `[ [` $i_1, \ldots, i_N$ `] :  [` $k_1, \ldots, k_N$ `] :  [` $s_1, \ldots, s_N$`] ].`

  and

  `[` $i_1 : k_1, \ldots, i_N : k_N$`]`

  is the same as

  `[ [` $i_1, \ldots, i_N$ `] :  [` $k_1, \ldots, k_N$ `] ].`

- RD`.arity` $= N$, and is a manifest constant.

- The expression RD`.min()` yields a `Point<`N`>` such that RD`.min()[`k`]` is the minimum over all p in RD of p`[`k`]`. Likewise for RD`.max()`. For empty domains, RD`.min()` yields a point all of whose coordinates are `Integer.MAX_VALUE`, and RD`.max()` yields a point all of whose coordinates are `Integer.MIN_VALUE`.

- RD`.boundingBox()` yields

  `[` RD`.min() :  ` RD`.max() ].`

  For `RectDomains` R with unit stride, R`.boundingBox()=`R.

- R`.stride()` yields the minimal `Point<`N`>`, s > `Point<`N`>`.all(0) such that R `=` `[`$p_0 : p_1 : s$`]` for some p_0 and p_1. (This need not be the same as the stride used to construct R in the first place: for example,

  ```
  ([ 0:1:2, 0:1:2 ]).stride()
  ```

  is `[1,1]`, not `[2,2]`.)

- RD`.size()` is the cardinality of RD (the number of Points it contains). The predicate RD`.isNull()` is true iff RD`.size()` $= 0$.

- R`.permute(`p_1`)` is the `RectDomain<`N`>` consisting of all points p`.permute(`p_1`)` for p in RD.

- The operations `+`, `-`, and `*` are defined between any combination of `RectDomain<N>`s and `Domain<N>`s. They stand for union, difference, and intersection of the sets of elements in the operand domains. The intersection of two `RectDomain<N>`s yields a `RectDomain<N>`. All other operations and operands yield `Domain<N>`s.

- For a `Point<N>`, p, the expressions $RD{+}p$, $RD{-}p$, $RD{*}p$, and RD/p compute the domains
$$\{d | d = d' \oplus p, \text{ for some } d' \in RD\}$$
where $\oplus$ = `+`, `-`, `*`, or integer division rounded toward $-\infty$ (unlike ordinary integer division, which rounds toward 0). Divisions require that each $p[i]$ be non-zero, and, if RD is a `RectDomain`, that each RD`.stride(`i`)` either be divisible by $p[i]$ or less than $p[i]$; it is an error otherwise. If RD is a `RectDomain`, so is the result.

- The operations `<`, `==`, `!=`, `>`, `<=`, and `>=` are defined between `RectDomain`s and between `Domain`s and represent set comparisons (`<` is strict subset, etc.).

- The expression RD`.contains(`p`)`, for `Point<N>` p, is true iff $p \in RD$.

- The expression R`.accrete(`k`, `dir`, `s`)` gives the result of adding elements to R on the side indicated by direction dir, expanding it by $k \geq 0$ strides of size $s > 0$ (all arguments but R are integers). That is, it computes

  $R{+}(R{+}$`Point<N>.direction`$(dir, s)){+}\ldots{+}(R{+}$`Point<N>.direction`$(dir, s \cdot k))$

  and returns the result (always rectangular) as a `RectDomain`. It is an error if R could not have been constructed with a stride of s in direction dir, so that the resulting set of elements would not be a `RectDomain`. [It is not possible always to get the stride from R, since it is not well-defined when R is degenerate (empty or having only one value for index k of its `Point`s.] The argument s may be omitted; it defaults to 1. Requires that $1 \leq |dir| \leq N$.

- The expression R`.accrete(`k`, `S`)` gives the result of expanding R on all sides by $k \geq 0$, as for the value V computed by the sequence

  ```
  V = R.accrete(k, 1, S[1]); V = V.accrete(k, -1, S[1]);
  V = V.accrete(k, 2, S[2])....
  ```

  The argument S is a `Point` with the same arity as R. It may be omitted, in which case it defaults to `all(1)`.

- The expression R`.shrink(`k`, `dir`)` gives the result of shrinking R on the side indicated by direction dir by $k \geq 0$ strides of size R`.stride(`$|dir|$`)` That is, it computes

  $R{*}(R{+}$`Point<N>.direction`$(dir, s)){*}\ldots{*}(R{+}$`Point<N>.direction`$(dir, -k \cdot s))$.

where s is R`.stride(`$|dir|$`)`. Requires that $1 \leq |dir| \leq N$.

- The expression R`.shrink(`k`)` gives the result of shrinking R on all sides by $k \geq 0$ strides, as for the value V computed by the sequence

  V = R`.shrink(`k`, 1).shrink(`k`, -1).shrink(`k`, 2)....`

- The expression R`.border(`k`, `dir`, `$shift$`)` consists, informally, of the k-thick ($k \geq 1$) layer of index positions on the side of R indicated by dir, shifted by $shift$ positions in direction dir. Thus,

  R`.border(1, `dir`, 0)`

  is the layer of cells on the face of R in direction dir, while

  R`.border(1, `dir`, 1)`

  is the layer of cells just over that face (outside the interior of R). More formally, it is

  R`.accrete(`k`, `dir`) - `R` + Point<`N`>.direction(`dir`, `$shift$`-`k`)`

  Requires that $k \geq 0$, $0 < |dir| \leq N$. As shorthand,

  R`.border(`k`, `dir`) = `R`.border(`k`, `dir`, 1)`

  and

  R`.border(`dir`) = `R`.border(1, `dir`, 1).`

- The expression R`.slice(`k`)`, where $0 < k \leq N$, and $N > 1$ is a `RectDomain<`$N-1$`>` consisting of the set

$$\{[p_1, \ldots, p_{k-1}, p_{k+1}, \ldots, p_N] \mid p = [p_1, \ldots, p_n] \in R\}.$$

- The expression D`.RectDomainList()` returns a one-dimensional array (see §4.2) of type `RectDomain<`N`>[1d]` containing zero or more disjoint, non-null domains whose union (treated as `Domain<`N`>`s) is D.

- The expression `Domain<`N`>.toDomain(`X`)`, where X is of type `RectDomain<`N`>[1d]` and has disjoint members, yields a `Domain<`N`>` consisting of the union of the elements of X.

- The expression D.PointList() returns an array of type `Point<`N`>[1d]` of distinct points consisting of all the members of D.

- The expression `Domain<`N`>.toDomain(`X`)`, where X is of type `Point<`N`>[1d]` and has distinct members, yields a `Domain<`N`>` whose members are the elements of X.

- The expression RD`.toString()` yields a text representation of RD.

- The expression `Domain<`N`>.setRegion(`*reg*`)`, where *reg* is a `Region`, is described in §6.3.2.

Control Structures: The construct

`foreach (`p `in` RD`)` S

for RD any kind of domain, executes S repeatedly, binding p to the points in R in some unspecified order. The scope of the control variable p is S. It is constant (`final`) within its scope. The control constructs `break` and `continue` function in `foreach` loops analogously to other loops.

Chapter 4

New Type Constructors

4.1 Syntax

Titanium modifies Java syntax to allow for *grid types* (§4.2), and the qualifiers `local` (§6.1), `nonshared` (§6.2), `polyshared` (§6.2) and `single` (§9.3.1).

Type:
  QualifiedBaseType ArraySpecifiers$_{opt}$

QualifiedBaseType:
  BaseType Qualifiers$_{opt}$

ArraySpecifiers:
  ArraySpecifiers ArraySpecifier
  ArraySpecifier

ArraySpecifier:
  `[]` *Qualifiers*$_{opt}$
  `[` *IntegerConstantExpression* `d ]` *Qualifiers*$_{opt}$

Qualifiers:
  Qualifier Qualifiers
  Qualifier

Qualifier: `single` | `local` | `nonshared` | `polyshared`

BaseType: *PrimitiveType* | *ClassOrInterfaceType* where *PrimitiveType* and *ClassOrInterfaceType* are from the standard Java syntax. The grouping of qualifiers with the types they modify is as suggested by the syntax: In *QualifiedBaseType,* the qualifiers modify the base type. Array specifiers apply to their *QualifiedBaseType* from right to left: that is, '`T [1d][2d]`' is "1-D array of (2-D arrays of T)." The qualifiers in the array specifiers apply to the type resulting from the immediately preceding array specification. That is, for qualifiers Q_1, Q_2, Q_3,

`Object` Q_3 `[]` Q_1 `[]` Q_2 `V;`

defines `V` to be a Q_1 array of Q_2 arrays of Q_3 `Object`s. We call Q_1 the *top-level qualifier,* and Q_3 the *base qualifier.*

The qualifier **single** is outwardly contagious. That is, the type "array of single T" (`T single [...]`) is equivalent to "single array of single T" (`T single [...]  single`).

Atomic types. An *atomic type* is either a primitive type (`int`, `double`, etc.), or an immutable class (see §5) whose fields all have atomic type.

4.2 Arrays

A Java array (object) of length N—hereafter called a *standard array*—is an injective mapping from the interval of non-negative integers $[0, N)$ to a set of variables, called the *elements* of the array. Titanium extends this notion to *grid arrays* or *grids;* an N-dimensional grid is an injective mapping from a `RectDomain<`N`>` to a set of variables. As in Java, the only way to refer to any kind of array object—standard or grid—is through a pointer to that object. Each element of a standard array resides in (is mapped to from) precisely one array[1]. The elements of a grid, by contrast, may be shared among any number of distinct grids. That is, even if the array pointers `A` and `B` are distinct, `A[p]` and `B[p]` may still be the same object. We say then that `A` and `B` *share* that element.

As for other objects, The value **null** is a legal value for a grid variable, and it is legal to compare grid quantities (using `==` or `!=`) against the literal **null**. However, it is *not* legal to compare non-null grids with `==` or `!=`. It is also illegal to cast grid values to the type `Object`.

For a non-grid type T, the type "N-dimensional grid with element type T" is denoted

T`[`N`d]`

[1]This does *not* mean that there is only one name for each element. If `X` and `Y` are arrays (of any kind), then after '`X=Y;`', `X[p]` and `Y[p]` denote the same variable. That is an immediate consequence of the fact that arrays are always referred to through pointers.

where N is a positive manifest integer constant. When that constant is an identifier, it must be separated from the 'd' by a space[2]. To declare a variable that may reference two-dimensional grids of doubles, and initialize it to a grid indexed by the RectDomain<2> D, one might write

```
double[2d] A = new double[D];
```

For the type "N_0-dimensional grid whose elements are N_1-dimensional grids... whose elements are of type T," we write

T [N_0d] [N_1d] $\cdots$.

There is a reason for this irregularity in the syntax (where one might have expected a more compositional form, in which the dimensionalities are listed in the opposite order). The idea is to make the order of indices consistent between type designations, allocation expressions, and array indexing. Thus, given

```
double[1d][2d] A = new double[D1][D2];
```

we access an element of A with

```
A[p1][p2]
```

where D1 is a RectDomain<1>, D2 a RectDomain<2>, p1 a Point<1>, and p2 a Point<2>[3].

Two grid types are assignment compatible only if they are identical, aside from narrowing and widening conversions on top-level qualifiers (see §6.1 and §6.2.4). This is in contrast to the restriction for Java arrays, which is as in standard Java: assignment conversion of one array-of-reference type to another is possible if the element types are assignment convertible.

Grid types are (at least for now) not quite complete Java Objects, in that they may not be coerced to type Object. This restriction aside, they are otherwise reference types, and are subject to reference qualification (see §4).

4.2.1 Operations:

In the following, take $p, p_0, \ldots$ to be of type Point<N>, A to be a grid of some type T [Nd], and D to be a RectDomain<N>.

[2] It is true that when N is an integer literal, Nd is syntactically indistinguishable from a floating-point constant in Java. However, in this context, such a constant would be illegal.

[3] Take these examples with a grain of salt. In general, it is preferable to use a RectDomain<3> index set in preference to the array-of-arrays seen here, if the algorithm justifies it, because compilers are apt to do better with the former.

- A.`domain()` is the domain (index set) of A. It is a `RectDomain<`N`>`.

- A`[`p`]` denotes the element of A indexed by p, assuming that p is in A.`domain()`. It is an lvalue—an assignable quantity—unless A is a global array of local references, in which case it is unassignable.

- The expression A`.copy(`B`)` copies the contents of the elements of B with indices in `A.domain()*B.domain()` into the elements of A that have the same index. It is illegal if A and B do not have the same grid type. It is also illegal if A is a global array whose element type has local qualification (it is easy to construct instances in which such a copy would be unsound). Finally, it is illegal if B resides in a private region, A resides in a shared region (see §6.3), and the elements of B have a non-atomic type (see §4.1). (This last provision is a conservative restriction to prevent situations where objects allocated in shared regions contain references to objects in private regions.) It *is* legal for A and B to overlap, in which case the semantics are as if B were first copied to a (new) temporary before being copied to A. See also the operations for sparse-array copying described in §12.11.

- A`.arity` is the value of A`.domain().arity` when `A` is non-null, and is a manifest constant.

- If $i_1, \ldots, i_N$ are integers, then A`[`$i_1, \ldots, i_N$`]` is equivalent to A`[ [`$i_1, \ldots, i_N$`] ]`. (Syntactic note: this makes `[...]` similar to function parameters; applications of the comma operator must be parenthesized, unlike C/C++)

- The following operations provide remappings of arrays.

  – A`.translate(`p`)` produces a grid, B, whose domain is `A.domain()+`p, such that B`[`p`+`x`]` aliases A`[`x`]`.

  – A`.restrict(`R`)` produces the restriction of A to index set R. R must be a `RectDomain<`N`>`.

  – A`.inject(`p`)` produces a grid, B, whose domain is `A.domain()*`p, such that B`[`p`*`x`]` aliases A`[`x`]`.

  – A`.inject(`p`).project(`p`)` produces A. For other arguments, `project` is undefined.

  – A`.slice(`k, j`)` produces the grid, B, with domain A`.domain().slice(`k`)` such that

  $$B\texttt{[[}p_1, \ldots, p_{k-1}, p_{k+1}, \ldots, p_n\texttt{]]} \texttt{ = } A\texttt{[[}p_1, \ldots, p_{k-1}, j, p_{k+1}, \ldots, p_n\texttt{]]}.$$

  It is an error if any of the index points used to index A are not in its domain, or if A`.arity()`≤ 1.

- `A.permute(`p`)`, where p is a permutation of $1, \ldots, N$, produces a grid, B, where A`[`$i_1, \ldots, i_N$`]` aliases B`[`$i_{p[1]}, \ldots, i_{p[N]}$`]`.

- `A.set(`v`)`, where v is an expression of type T, sets all elements of A to v.
- The I/O operations described in §12.12.1.
- The sparse-copying operations described in §12.11.

4.2.2 Overlapping Arrays.

As for any reference type in Java, two grid variables can contain pointers to the same grid. In addition, several of the operations above produce grids that reference the same elements. The possibility of such *overlap* does not sit well with certain code-generation strategies for loops over grids. Using only intraprocedural information, a compiler can sometimes, in principle, determine that two grid variables do not overlap, but the problem becomes complicated in the presence of arbitrary data structures containing grid pointers, and when one or more grid variable is a formal parameter.

For these reasons, Titanium has a few additional rules concerning grid parameters:

- Formal grid parameters to a function (including the implicit `this` in the case of methods defined on grids) may not overlap unless otherwise specified—that is, given two formals F_1 and F_2, none of the variables $F_1[p_1]$ may be the same as $F_2[p_2]$. It is an error otherwise.
- The qualifier '`overlap(`F_1`,`F_2`)`' immediately following a method header, where F_1 and F_2 name formal parameters of that method, means that the restriction does not apply to F_1 and F_2. (There is no restriction that F_1 and F_2 have the same type or even that they be grids. When they are not grids of the same type, however, the qualifier has no effect.)
- To specify that two grid variables X and Y do not overlap at some point in a program, the programmer inserts the call

  X`.noOverlap(`Y`)`.

  This is a method on grids that behaves somewhat as if defined

  `public void noOverlap (T[] B) {}`,

  which, by the rules above, does nothing and requires that `B` and `this` not overlap. The qualifier "somewhat" is needed in this description because in fact the call is legal regardless of the element type or local qualification of any of the operands.

4.2.3 Restrictions on Standard Arrays

The possibilities of local qualification and of residence in private regions require additional restrictions on the standard array method `System.arraycopy`, analogous to those on the `.copy` operation for grids. For standard arrays A and B, the call

```
System.arraycopy (A, k0, B, k1, len)
```

is illegal if A is a global array whose element type has local qualification. It is also illegal if A resides in a private region, B resides in a shared region (see §6.3), and the elements of A have a non-atomic type (see §4.1).

Chapter 5

Immutable Classes

Immutable classes (or *immutable types*) extend the notion of Java primitive type to classes. An immutable class is a final class that is not a subclass of Object and whose non-static fields are final. It is declared with the usual class syntax and an extra modifier

```
immutable class C { ... }
```

Non-static fields are implicitly `final`, but need not be explicitly declared as `final`.

Because immutable classes are not subclasses of any other class, their constructors may not call `super()` explicitly, and, contrary to the usual rule for Java classes other than Object, do not do so implicitly either.

There are no type coercions to or from any immutable class, aside from those defined on standard types in the Titanium library (see §3.2). The standard classes `Point<`N`>`, `RectDomain<`N`>`, and `Domain<`N`>` are immutable.

The value `null` may not be assigned to a variable of an immutable class. The initial value of a variable of immutable class `T` is `new T()`[1]. Initialization of the fields in objects of these types follows the rules of Java 1.2.

Circular chains of immutable types are disallowed. That is, no immutable type may contain a subcomponent of its own type. Here, a *subcomponent* is a field, or a subcomponent of a field, where the field has an immutable type.

By default, the operators `==` and `!=` are defined by comparison of the fields of the object. Any `void finalize()` method supplied with an immutable object is ignored.

[1]This is not quite sufficient, but suffices for non-pathological programs. In standard Java, the effect of accessing a field before it has been properly initialized is well-defined (even when it is illegal!) in such a way as to be easy to implement (i.e., zero out all storage immediately upon allocation). The analogous implementation for a field of immutable class, assuming that objects of that class are unboxed, has a peculiar semantic description: the field is initialized to point to an *uninitialized* object in which all fields have their default values. This object is then initialized at the normal time (i.e., at the time its constructor would have executed had it been of an ordinary class).

As a consequence of these rules, it is impossible, except in certain pathological programs, to distinguish two objects of an immutable class that contain equal fields. The compiler is free to ignore the possibility of pathology and unbox immutable objects.

The '+' operator (concatenation) on type `String` is extended so that if S is a string-valued expression and X has an immutable type, then S`+`X is equivalent to S`+`X`.toString()` and X`+`S is equivalent to X`.toString()+`S. These expressions are therefore illegal if there is no `toString` method defined for X, or if that method does not return a `String` or `String local`.

Chapter 6

Pointers and Storage Allocation

6.1 Demesnes: local vs. global pointers

In Titanium, the set of all memory is the union of a set of local memories, called *demesnes* here to give them a veneer of abstraction. Each object resides in one demesne. Each *process* (§9) is associated with one demesne—called simply the *demesne of the process*. A local variable resides in the demesne of the process that allocates that variable. An object created by **new** and the fields within it reside in the demesne of the process that evaluates the **new** expression.

The intent is that on a uniprocessor implementation, there will be a single demesne, and likewise on a shared-memory multiprocessor. On a pure distributed-memory multiprocessor, there would be a single demesne corresponding to each processor. Finally, on a distributed cluster of shared-memory multiprocessors, there would be one demesne for the processes on each shared-memory node.

The static types ascribed to variables (locals, fields, and parameters) containing reference values and to the return values of functions that return reference values are either *global* or *local*. A variable having a local type will contain only null or pointers whose demesnes are the same as that of the variable. A pointer contained in a variable with global type may have any demesne. A locally qualified variable may be assigned only a value whose type is (statically) local. The purpose of the distinction between local and global references is to improve performance. Dereferencing a global reference requires a test to see whether the referenced datum is accessible with a native pointer; communication is needed if it is not. Local references are for those data known to be accessible with a native pointer. Global references can be used anywhere but local references don't travel well.

Standard Java type designators for reference types denote global types. The modifier keyword `local` indicates a local reference. For examples:

```
Integer i1;                   /* i is a global reference */
```

```
Integer local i2;            /* i is a local reference */
int local i3;                /* illegal: int not a reference type */
```

Reference types used in static fields may never be local. For grids, there is an additional degree of freedom:

```
/* A1 is a global pointer to an array of variables that may reside
 * remotely (i.e., in a different demesne from the variable A1). */
int[1d] A1;
/* A2 is a local pointer to an array of variables that reside
 * locally (in the same demesne as A2). */
int[1d] local A2;

/* A3 is a local pointer to an array of variables that reside
 * locally and contain pointers to objects that may reside
 * remotely. */
Integer [1d] local A3;
/* A4 is a local pointer to an array of variables that reside
 * locally and contain pointers to objects that reside locally */
Integer local [1d] local A4;
/* A5 is a global pointer to an array of variables that may
 * reside remotely and contain pointers to objects that
 * may reside remotely */
Integer [1d] A5;
/* A6 is a global pointer to an array of variables that may
 * reside remotely and contain pointers to objects that reside
 * in the same demesne as that array of variables. */
Integer local [1d] A6;
```

We refer to a reference type apart from its local/global attribute as its *object type*.

Coercions between reference types are legal if, first, their object types obey the usual Java restrictions on conversion (plus Titanium's more stringent rules on arrays). Second, a reference value may only be coerced to have a local type (by means of a cast) if it is null or denotes an object residing in the demesne of the process performing the coercion. It is an error to execute such a cast otherwise. Coercions from local to corresponding global types are implicit (they extend assignment and method invocation conversion). Global to local coercions must be expressed by explicit casts.

If a field selection `r.a` or `r[a]` yields a reference value and `r` has static global type, then so does the result of the field selection.

All reference classes support the following operations:

`r.creator()` Returns the identity of the lowest-numbered process whose demesne contains the object pointed to by `r`. NullPointerException if `r` is null. This number may differ from the identity of the process that actually allocated the object when multiple processes share a demesne.

`r.isLocal()` Returns true iff `r` may be coerced to a local reference. This returns the same value as `r instanceof T local`, assuming `r` to have object type `T`. On some (but not all) platforms `r.isLocal()` is equivalent to `r.creator() == Ti.thisProc()`.

`r.regionOf()` See §6.3.2.

`r.clone()` Is as in Java, but with local references inside the object referenced by `r` set to null. The result is a global pointer to the newly created clone, which resides in the same region (see §6.3.2) as the object referenced by `r`. This operation may be overridden.

`r.localClone()` Is the default `clone()` function of Java (a shallow copy), except that `r` must be local. The result is local and in the same region (see §6.3.2) as the object referenced by `r`.

To indicate that the special variable `this` in a method body is to be a local pointer, label the method local by adding the `local` keyword to the method qualifiers:

```
public local int length () {...}
```

Otherwise `this` is global. If necessary, the value for which a method is invoked is coerced implicitly to be global. A static method may not be local.

6.2 Data Sharing

In Titanium, the type of any reference includes information about how the referent is shared among multiple processes. The `nonshared` and `polyshared` qualifiers encode this information. By default, most data is assumed to be shared; there is no explicit `shared` qualifier. A `nonshared` qualifier declares that the reference addresses data that is not shared: it is only accessible by processes within the same demesne as the data itself. A `polyshared` qualifier indicates that the reference addresses data that may be shared or may be non-shared.

6.2.1 Basic Syntax

The `nonshared` and `polyshared` qualifiers can modify any reference type, including named reference classes, named interfaces, Java arrays, and Titanium arrays. Sharing qualifiers on arrays may be set independently for elements and for the array as a whole. Thus:

```
/* a shared object */
Object x;

/* a non-shared object */
Object nonshared y;

/* either a shared or a non-shared array of non-shared objects */ \\
Object nonshared [] polyshared z;
```

Sharing qualifiers may modify types in any context where types are expected, including field declarations, variable declarations, formal parameter declarations, method return type declarations, catch clauses, cast expressions, `instanceof` expressions, and template parameters. The `nonshared` qualifier can be used in allocation expressions to allocate non-shared data rather than the default shared data. However, the `polyshared` qualifier may not be used to directly allocate data with unknown sharing; this is a compile-time error: allocated data must be either shared or non-shared at the topmost level. Thus:

```
/* ok: a shared object */
Object a = new Integer(6);

/* ok: a non-shared object */
Object nonshared b = new Integer nonshared (6);

/* error: cannot allocate polyshared data */
Object polyshared z = new Integer polyshared (6);

/* ok: a shared array of polyshared objects */
Object polyshared [] c = new Object polyshared [10];

/* ok: a non-shared array of polyshared objects */
Object polyshared [] nonshared d = new Object polyshared [10] nonshared;

/* error: cannot allocate polyshared data */
Object polyshared [] polyshared e = new Object polyshared [10] polyshared;
```

Reference types can have zero or one sharing qualifier: it is an error to qualify any type as both `nonshared` and `polyshared`. Primitive and immutable types may not be qualified as either `nonshared` or `polyshared`.

6.2.2 Methods

Within a reference class, a sharing qualifier may also appear among the qualifiers for a non-static method or constructor, in which case it applies to the implicit `this` parameter within the method or constructor body. It is an error to add any sharing qualifier to a static method, immutable method, or immutable constructor. It is an error to add more than one sharing qualifier to a reference class method.

Types that vary only in their sharing qualifiers are considered distinct types for purposes of method overloading and method overriding. This applies equally to formal method parameters, method return types, and the `this` qualifier.

6.2.3 Implicit Sharing Qualifiers

In several instances, the sharing status of entities is implicit:

- Within field initialization expressions of reference classes, `this` is assumed to be polyshared.
- If the compiler provides a default constructor (Java spec §8.8.7), then this constructor is assumed to be polyshared.
- String literals are assumed to be shared.
- The null type can be converted to any shared, non-shared, or polyshared reference type, so the sharing qualification of the `null` literal is unspecified and irrelevant.

In all other contexts, unqualified types are assumed to be shared.

6.2.4 Conversion

Standard Java conversion rules are modified as follows.

All widening reference conversions (Java spec §5.1.4) are restricted to apply only when at least one of the following conditions hold:

- the source type and destination type have identical top-level sharing qualifiers (that is, the sharing qualifiers that apply to the types as a whole—as opposed to the types of components—are identical).
- the source type is the null type
- the destination type's top-level sharing qualifier is `polyshared`

Widening reference conversion of array types is further constrained to apply only when the top-level sharing qualifiers of the element types are identical. For example:

```
/* ok: (top-level) destination type is polyshared */
Object polyshared o1 = new Integer nonshared (7);

/* ok: top-level destination type is polyshared, element types
 * match.  */
Object nonshared [] polyshared o2 =
   new Object nonshared [10] nonshared;

Object nonshared [] polyshared [] nonshared o3 =
   new Object nonshared [10] nonshared [10] nonshared;

/* error: top-level qualifiers on elements do not match:
 * (polyshared vs. non-shared) */
Object polyshared [] o4 = new Integer nonshared [];

Object nonshared [] nonshared [] polyshared o3 =
   new Object nonshared [10] nonshared [10] nonshared;
```

All narrowing reference conversions (Java spec §5.1.5) are restricted to apply only when the source type and destination type have identical top-level sharing qualifiers. Narrowing reference conversion of array types is further constrained to apply only when the top-level sharing qualifiers of the element types are identical. Informally, one cannot convert polyshared data back to shared or non-shared data, even using a run time test.

6.2.5 Restricted Operations

Non-shared data must only be used by processes in the same demesne. Local references carry no special restrictions, as the data to which they refer is already known to reside in the appropriate demesne. Any reference to shared data is similarly unconstrained. However, a global reference to non-shared or polyshared data is restricted. If `p` is a global reference to non-shared or polyshared data, then the following operations are forbidden:

- reading the value of any field of `p`;
- reading the value of any element of `p`, if `p` is an array;
- assigning into any field of `p`;
- assigning into any element of `p`, if `p` is an array;
- calling any non-static method of `p`;

- evaluating `p instanceof T` for any type `T`;
- performing a narrowing reference conversion of `p` to a global type;
- using a `synchronized` statement to acquire the mutual exclusion lock of `p`;
- using `p` within a string concatenation expression.

The restriction on narrowing reference conversion does allow casting to a local type. It merely forbids checked casts that do *not* simultaneously recover localness.

6.2.6 Early Enforcement

Titanium contains two alternative definitions of sharing. Late enforcement is the more relaxed of the two, and entails only those restrictions already listed above. Early enforcement entails the following additional restrictions:

- Any type that is non-shared or polyshared must also be local; global pointers may only address shared data.
- If any use of a named class is (implicitly) qualified as shared, then all fields embedded within that class must be qualified as shared. "Embedded" here is defined as:
  - If class C defines field $C.f$, then field $C.f$ is embedded within class C.
  - If class C has superclass D, then all fields embedded within class D are also embedded within class C.
  - If class C has embedded field $B.f$, and $B.f$ has immutable type I, then fields embedded within immutable class I are also embedded within class C.
- If any use of an array type is (implicitly) qualified as shared, then the elements of the array must be shared as well.

6.3 Region-Based Memory Allocation

Java uses garbage collection to reclaim unreachable storage. Titanium retains this mechanism but also includes a more explicit (but still safe) form of memory management: *region-based* memory allocation.

In a region-based memory allocation scheme, each allocated object is placed in a program-specified *region*. Memory is reclaimed by destroying a region, freeing all the objects allocated therein. A simple example is shown in Figure 6.3. Each iteration of the loop allocates a small array. The call `r.delete()` frees all arrays.

```
class A {
  void f()
  {
    PrivateRegion r = new PrivateRegion();

    for (int i = 0; i < 10; i++) {
      int[] x = new (r) int[i + 1];
      work(i, x);
    }
    try {
        r.delete();
    }
    catch (RegionInUse oops) {
        System.out.println("oops - failed to delete region");
    }
  }

  void work(int i, int[] x) { }
}
```

Figure 6.1: An example of region-based allocation in Titanium.

A region r can be deleted only if there are no *external* references to objects in r (a reference external to r is any pointer not stored within r). A call to `r.delete()` throws an exception when this condition is violated.

6.3.1 Shared and Private Regions

There are two kinds of regions: *shared* regions and *private* regions. Objects created in a shared region are called *shared-region objects*; all other objects are called *private objects*. Garbage-collectible objects are taken to reside in an anonymous shared region. It is an error to store a reference to a private object in a shared-region object. It is also an error to broadcast or exchange a private object. As a consequence, it is impossible to obtain a private pointer created by another process.

All processes must cooperate to create and delete a shared region, each getting a copy of the region that represents the same, shared, pool of space. The copy of the shared region object created by a process p is called the *representative* of that region in process p (see the `Object.regionOf` method below). Creating and deleting shared regions thus behaves like a barrier synchronization and is an operation with global effects (see §9.3.1).

A region is said to be *externally referenced* if there is a reference to an object allocated in it that resides in

- A live local variable;
- A static field;
- A field of an object in another region.

The process of attempting to delete a region r proceeds as follows:

1. If r is externally referenced, throw a `ti.lang.RegionInUse` exception.
2. Run the `finalize` methods of all objects in r for which it has not been run[1].
3. If r is now externally referenced, throw a `ti.lang.RegionInUse` exception.
4. Free all the objects in r and delete r.

Garbage-collected objects behave as in Java. In particular, deleting such objects differs from the description above in that finalization does not wait for an explicit region deletion.

6.3.2 Detailed Specification of Region-Based Allocation Constructs

Shared regions are represented as objects of the `ti.lang.SharedRegion` type, private regions as objects of the `ti.lang.PrivateRegion` type. The signature of the types is as shown in Figure 6.2.

The Java syntax for `new` is redefined as follows (T is a type distinct from `ti.lang.PrivateRegion` and `ti.lang.SharedRegion`):

- `new ti.lang.PrivateRegion()` or `new ti.lang.SharedRegion()`: creates a region containing only the object representing the region itself.
- `new T...`: allocate a garbage-collected object, as in Java.
- `new (expression) T...` creates an object in the region specified by `expression`. The static type of `expression` must be assignable to `ti.lang.Region`. At runtime the value v of `expression` is evaluated. If v is:
  - `null`: allocate a garbage-collected object, as in Java.
  - an object of type `ti.lang.PrivateRegion` or `ti.lang.SharedRegion`: allocate an object in region v.

[1] As of this writing, finalization is not implemented.

```
package ti.lang;

final public class PrivateRegion extends Region
{
  public PrivateRegion() { }
  /** Run finalization on all unfinalized objects in THIS.
   *  Frees all resources used to represent objects in THIS.
   *  Throws RegionInUse if THIS is externally referenced
   *  before or after finalization. */
  public void delete() throws RegionInUse;
};

final public class SharedRegion extends Region
{
  public single SharedRegion() { }
  /** See PrivateRegion.delete, above. */
  public single void delete() throws RegionInUse single;
};

abstract public class Region
{
};
```

Figure 6.2: Library definitions related to regions.

– In all other cases a runtime error occurs.

The class `java.lang.Object` is extended with the following method:

```
public final ti.lang.Region local regionOf();
```

This returns the region of the object, or `null` for garbage-collected objects. For shared-region objects, the local representative of the shared region is returned.

The expression `Domain<`N`>.setRegion(`*reg*`)`, where *reg* is a `Region`, dynamically causes *reg* to become the `Region` used for allocating all internal pointer structures used in representing domains (until the next call of `setRegion`). A null value for `reg` causes subsequent allocations to come from garbage-collected storage. Returns the previous value passed to `setRegion` (initially `null`). The value of `N` is irrelevant; all general domains are allocated in the same region.

Chapter 7

Templates

Titanium uses a "Templates Light" semantics, in which template instantiation is a somewhat augmented macro expansion, with name capture and access rules modified as described below.

7.1 Instantiation Denotations

Define

TemplateInstantiation:
    `template` *Name* `"<"` *TemplateActual* { `","` *TemplateActual* }`*` `">"`
TemplateActual:
    Type | *AdditiveExpression*

where the AdditiveExpression is a ConstantExpression. Resolution of Name is as for type names. [Note: We use AdditiveExpression to prevent non-LALRness with `<` and `>` operators.] It is devoutly to be hoped that the bogus `template` keyword can be eliminated from instantiations.

7.2 Template Definition

TemplateDeclaration:
    TemplateHeader ClassDeclaration
    TemplateHeader InterfaceDeclaration
TemplateHeader:

```
    template "<" TemplateFormal { "," TemplateFormal }* ">"
TemplateFormal:
    class Identifier
    BasicType Identifier
```

The first form of TemplateFormal allows any type as argument; the second allows ConstantExpressions of the indicated type.

7.3 Names in Templates

A template belongs to a particular package, as for classes and interfaces. Access rules for templates themselves are as for similarly modified classes and interfaces.

Template instantiations belong to the same package as the template from which they are instantiated. As a result, it is essentially useless to instantiate a template from a different package except with public classes and interfaces[1].

Names other than template parameters in a template are captured at the point of the template definition. Names in a TemplateActual (and at the point it is substituted for in a template instantiation) are resolved at the point of instantiation.

7.4 Template Instantiation

References to TemplateInstantiation are allowed as Types. They are not allowed in `extends` or `implements` clauses. Instantiations that cause an infinite expansion or a loop are compile-time errors. Inside a template, one may refer to the "current instantiation" by its full name with template parameters; or by the template's simple name. The constructor is called by the simple name. Template formals may not be used in `extends` or `implements` clauses.

```
template<class T> class List {
    ...
    List (T head, List tail) {...}

    List tail() { ... }
}
```

[1] An alternative rule (not currently implemented) states that template instantiations have package-level access to all classes and interfaces mentioned in the template actuals, so that the expansion of a template might be illegal according to the usual rules (e.g., the template expansion could reside in package `P` and yet contain fields whose types were non-public members of package `Q`). The rationale for this alternative is that otherwise, a package of utility templates would be useless unless one was willing to make public all classes used as template parameters.

or

```
template<class T> class List {
    ...
    List (T head, template List<T> tail) {...}

    template List<T> tail() { ... }
}
```

7.5 Name Equivalence

For purposes of type comparison, all simple type names and template names that appear as TemplateActuals are replaced by their fully-qualified versions. With this substitution, two type names are equivalent if their QualifiedName parts are identical and their TemplateActuals are identical (identical types or equal values of the same type).

7.6 Type Aliases

[NOTE: This section is as yet unimplemented.] The import clause is extended to include

ImportDeclaration:
  `import` *Identifier* `"="` *Type*`";"`

which introduces Identifier as a synonym for Type in the current compilation. The standard type import

```
import Qualifier.Name;
```

is thus shorthand for

```
import Name = Qualifier.Name;
```

Chapter 8

Operator Overloading

Titanium allows overloading of the following Java operators:

Unary prefix	`- ! ~`
Binary	`< > <= >= == !=`
	`+ - * / & | ^ % << >> >>>`
Matchfix	`[] []=`
Assignment	`+= -= *= /= &= |= ^= %= <<= >>= >>>=`

If $\oplus$ is one of these operators, then declaring `op`$\oplus$ produces a new overloading of that operator. No space is allowed between the keyword `op` and the operator name. These methods can be called like normal methods, e.g. `a.op+(3)`. There are no restrictions on the number of parameters, parameter types or result type of operator methods. In addition,

- An expression $E_1 \oplus E_2$, where $\oplus$ is binary, is equivalent to E_1.`op` $\oplus$ (E_2) as long as E_1 is not of a primitive type.
- An expression $\oplus E_1$, where $\oplus$ is unary, is equivalent to E_1.`op` $\oplus$ $()$, as long as E_1 is not of a primitive type.
- An expression $E_0[E_1, \ldots, E_n] = E$ is equivalent to E_0`.op[]=`$(E_1, \ldots, E_n, E)$.
- In other contexts, an expression $E_0[E_1, \ldots, E_n]$ is equivalent to E_0`.op[]`$(E_1, \ldots, E_n)$.

It is not possible to redefine plain assignment (`=`). It is possible to redefine the operator assignment methods, but the assignment remains: $E_1 \oplus$`=`E_2 is equivalent to E_1 `=` E_1`.op`$\oplus$`=`(E_2), except that expression E_1 is evaluated only once.

There is a conflict between Java's description of how the '`+`' operator works when the right argument is of type String and the description above, which arises whenever the programmer defines `op+` with an argument of type String. We resolve this by analogy with ordinary Java overloading of static functions. If class `A` defines `op+` on String, then `anA + aString` resolves to the user-defined '+', as if resolving a match between an overloaded two-argument function whose first argument is of type `Object` and one whose first argument is of type `A`.

Chapter 9

Processes

A *process* is essentially a thread of control. Processes may either correspond to virtual or physical processors—this is implementation dependent. Each process has a demesne (an area of memory heap; see §6) that may be accessed by other processes through pointers. Each process has a distinct non-negative integer *index*, returned by the function call `Ti.thisProc()`. The indices of all processes form a contiguous interval of integers beginning at 0.

Process teams. At any given time, each process belongs to a *process team*. The function `Ti.myTeam()` returns an `int[1d]` containing the indices of all members of the team in ascending order. Teams are the sets of processes to which broadcasts, exchanges, and barriers apply. Initially, all processes are on the same team, and all execute the main program from the beginning. This team has the index set `[0:Ti.numProcs()-1]`.

In the current version of Titanium, there is only one process team—the initial one. The process-team machinery in accordingly a bit heavier than needed. It will become useful should we decide to introduce the partition construct (see §11.1).

9.1 Interprocess Communication

Exchange. The member function `exchange`, defined on Titanium array types, allows all processes in a team to exchange data values with each other. The call

A`.exchange(`E`)`

acts as a barrier (see §9.2) among the processes with indices in `Ti.myTeam()`. Specifically, all of the processes in the team wait until Here, E is of some type T and A is a grid of T with an index set that is a superset of Ti.myTeam()`.domain()`. When all processes in a team have reached a call to `exchange`, then, assuming that all their arguments are of the same type, for each i in `Ti.myTeam()`'s domain, element i of each array is set to the argument E supplied by the process indexed by `Ti.myTeam()[`i`]`. It is an error if the processes reach different textual instances of `exchange`. It is illegal to exchange arrays of local pointers (that is arrays of a type qualified '**local**').

Thus, the code

```
double [1d] single [2d] x = new double[Ti.myTeam().domain()][2d];
x.exchange(new double [D]);
```

creates a vector of pointers to arrays, each on a separate processor, and distributes this vector to all processors.

Broadcast. The `broadcast` statement allows one process in a team to broadcast a value to all others. Specifically, in

`broadcast` E `from` p

—where E is an arbitrary value and p is the index of a process on the current process team—process p (only) evaluates E, and all other processes in the team wait at the `broadcast` (if necessary) until p performs the evaluation and then all return the value E. Processes may proceed even if some processes have not yet reached the broadcast and received the broadcast value. It is an error if the processes reach a different sequence of textual instances of the call. It is an error if the processes do not agree on the value p—in fact, p must be a single-valued expression (see §9.3.1). It is an error for the evaluation of E on processor p to throw an exception (which, informally, would keep one process from reaching the barrier).

9.2 Barriers

The call

```
Ti.barrier();
```

causes the process executing it to wait until all processes in its team have executed the same textual instance of the barrier call. It is an error for a process to attempt to execute a different sequence of textual instances of barrier calls than another in its team. Each textually distinct occurrence of `partition` and each textually distinct call on `exchange` waits on a distinct anonymous barrier.

9.3 Checking Global Synchronization

In SPMD programs, some portions of the data and control-flow are identical across all processes. In particular, the sequences of global synchronizations (barriers, broadcasts, etc.) in each process must be identical for the program to be correct. With the aid of programmer declarations, the Titanium compiler performs a (conservative) check for this correctness condition statically. To be able to perform this check, the compiler must know that certain parts of the program's data are replicated across all processes in the current process team, and that this replicated storage contains coherent values everywhere. By *coherent* we mean that values of primitive types are identical, and that values of reference types point to replicated objects that are of the same dynamic type. The programmer must use the type qualifier **single** to indicate what storage must be coherent.

The formal definition of "coherent" is in terms of pairs of storage locations: two storage locations a and b, residing in demesnes r_a and r_b respectively, and containing values of static type t are *consistent* if t is not **single**, or if:

- t is a primitive type: the values of a and b are identical;
- t is a java or titanium array type: a and b have the same bounds, the elements of a reside in r_a, the elements of b reside in r_b, and the corresponding elements are consistent;
- t is an object type (immutable or not): a and b have the same dynamic type, the object referred to by a resides in r_a, the object referred to by b resides in r_b, and corresponding non-static fields of a and b are consistent.

The compiler constrains all Titanium programs as follows. Given any program statement S, and the current process team P, and assuming

- all free variables of S and all static variables of the program have consistent values in all processes in P;
- `this` has a consistent value in all processes in P

then after the execution of S, and assuming that all processes in P terminate:

- all free variables of S and all static variables of the program still have consistent values in all processes in P;
- all processes have executed the same sequence of methods qualified with **single**—in particular this implies that all processes have executed the same sequence of global synchronization operations.

The following properties are important in checking that programs meet this constraint:

- an expression e is *single-valued* if it evaluates to a consistent value in all processes P that start executing e;
- a termination T (exception of type t, a break, continue or return) of a statement S is *universal* if either all processes P that start S terminate abruptly with termination T or no process P that starts S terminates abruptly with termination T—in addition, if the termination is an exception the value of the exception must be consistent in all processes in P;
- a statement has *global effects* if it or any of its substatements: assigns to any storage (variable, field or array element) whose type is t **single**, *may call* a method or constructor which has global effects, or is a `broadcast` expression;
- a method has *global effects* if any of the statements of its body have global effects; however, assignments to **single** local variables do not count as global effects;
- a native or abstract method has *global effects* if it is qualified with **single** (which is a new *MethodModifier* that can modify a method or constructor declaration);
- a constructor has *global effects* if any of the statements of its body have global effects; however, assignments to **single** local variables, or non-static **single** fields of the object being constructed do not count as global effects (the destination of these field assignments must be specified as an unqualified name or as **this.**name and the assignment must occur in the body of the constructor);
- a method call $e_1.m_1(\ldots)$ *may call* a method m_2 if m_2 is m_1, or if m_2 overrides (possibly indirectly) m_1

A `catch` clause in a `try` statement and the `throws` list of a method or constructor declaration indicate that an exception is universal by qualifying the exception type with **single**.

9.3.1 Single-valued expressions

In the following, the e_i are expressions, v is a non-static member and vs a static member. The following expressions are single-valued. In these descriptions, all instances of operators refer to built-in definitions; user-defined operators are governed by the same rules as function calls.

- constants;

- `this`;
- variables whose type is t **single**;
- $e_1.v$ if e_1 is single-valued and v is declared single;
- $e_1.vs$ if vs is a final field with an atomic type (§4.1).
- $e_1[e_2]$ if e_1 and e_2 are single-valued, e_1 is an array (standard or grid), and the type of the elements of e_1 is single;
- $e_1[e_2]$ if e_1 and e_2 are single-valued and e_1 is a Point.
- $e_1 \oplus e_2$, for e_1 and e_2 single-valued and $\oplus$ a built-in binary operator (likewise for unary prefix and postfix operators);
- $(T)e_1$ if T is single;
- e_1 `instanceof` T if e_1 is single-valued;
- $e_1 = e_2$ if e_2 is single-valued;
- $e_1 \oplus = e_2$ if e_1 and e_2 are single-valued and $\oplus =$ a built-in assignment operator;
- $e_1 ? e_2 : e_3$ if e_1, e_2 and e_3 are single-valued;
- $e_0.v(e_1, \ldots, e_n)$ if:
  - e_0 is single-valued
  - e_i is single-valued if the i'th argument of v is declared single;
  - the result of v is declared single;
- $e_0.vs(e_1, \ldots, e_n)$ if:
  - e_i is single-valued if the i'th argument of vs is declared single;
  - the result of vs is declared single;
- `new` $T(e_1, \ldots, e_n)$ if e_i is single-valued if the i'th argument of the appropriate constructor for T is declared single;
- `new` $T[e_1] \ldots [e_n]$ if $e_1, \ldots, e_n$ are single-valued (in this case the type is

  T `single` $[t_1]...[t_n]$

  where t_i is the type of e_i)

- $[e_1, \ldots, e_n]$ if $e_1, \ldots, e_n$ are single-valued;
- $[e_1 : e_2 : e_3]$ if e_1, e_2, e_3 are single-valued (and similarly for the other domain literal syntaxes);
- `broadcast` e_1 `from` e_2, if e_1 has a primitive type, or an immutable type with no reference-type fields.

Note. The rule for `broadcast` excludes reference values from single expressions, which may seem odd since the recipients of the broadcast will manifestly get the same value. This merely illustrates, however, the subtle point that "single" and "equal" are not synonyms. Consider a loop such as

```
x = broadcast E from 0;
while (x.N > 0) {
   ...
   Ti.barrier ();
   x.N -= 1;
}
```

(where '`x`' and the '`N`' field of its type are declared **single**). If we were to allow this, it is clearly easy to get different processes to hit the barrier different numbers of times, which is what the rules concerning **single** are supposed to prevent.

9.3.2 Restrictions on statements with global effects

The following restrictions on individual statements and expressions are enforced by the compiler:

- assignments to a local variable, method or constructor argument, field or array element whose type is single must be with a single-valued expression;
- if a method call $e_0.v(e_1, \ldots, e_n)$ may call method m_1 which has global effects then:
  - e_0 must be single-valued
  - e_i must single-valued if the i'th argument of v is declared single;
- in a method call $e_0.vs(e_1, \ldots, e_n)$ if vs has global effects then e_i must be single-valued if the i'th argument of vs is declared single;
- in an object allocation `new` $T(e_1, \ldots, e_n)$, if the constructor c is qualified with **single** then e_i must be single-valued if the i'th argument of c is declared single;

- in an array allocation `new` $T[e_1]$, if T is an immutable type and the zero argument constructor for T is qualified with **single** then e_1 must be single-valued;
- in `broadcast` e_1 `from` e_2, e_2 must be single-valued

9.3.3 Restrictions on control flow

The following restriction is imposed on the program's control flow: the execution of all statements and expressions with global effects must be controlled exclusively by single-valued expressions. The following rules ensure this:

- an `if` (or `?` operator) whose condition is not single-valued cannot have statements (expressions) with global effects as its 'then' or 'else' branch;
- a `switch` statement whose expression is not single-valued cannot contain statements with global effects;
- a `while`, `do/while` or `for` loop whose exit condition is not single-valued, and a `foreach` loop whose iteration domain(s) are not single-valued cannot contain statements or expressions with global effects;
- if the main statement of a `try` has non universal terminations then its `catch` clauses cannot specify any universal exceptions;
- associated with every statement or expression that causes a termination t is a set of statements S from the current method or constructor that will be skipped if termination t occurs. If the termination is not universal, then S must not contain any statements or expressions with global effects;

The rules for determining whether a termination is universal are essentially identical to the restrictions on statements with global effects: any termination raised in a statement that cannot have global effects is not universal. In addition:

- in `throw` e, the exception thrown is not universal if e is not single-valued;
- in a call to method or constructor v declared to throw exceptions of types $t_1, \ldots, t_n$, exception t_i is universal only if type t_i is **single** and the following conditions are met:
  - Normal method call $e_0.v(e_1, \ldots, e_n)$: if e_0 is single-valued and e_i is single-valued when the i'th argument of v is declared single;
  - Static method call $e_0.vs(e_1, \ldots, e_n)$: if e_i is single-valued when the i'th argument of vs is declared single;

– Object allocation `new` $T(e_1, \ldots, e_n)$: if e_i is single-valued when the i'th argument of the appropriate constructor for T is declared single;

– Immutable array allocation `new` $T[e_1] \ldots [e_n]$: if $e_1, \ldots, e_n$ are single-valued

9.3.4 Restrictions on methods and constructors

The following additional restrictions are imposed on methods and constructors:

- If a method is declared to return a single result, then the expression in all return statements must be single-valued. The return terminations must all be universal;
- Including `throws` t **single** in a method or constructor signature does not allow the method or constructor body to throw a non-universal exception assignable to t;
- A method f that overrides a method g must preserve the singleness of the method argument and result types.

9.4 Consistency of Shared Data

The consistency model defines the order in which memory operations issued by one processor are observed by other processors to take effect. Although memory in Titanium is partitioned into demesnes, the union of those demesnes defines the same notion of shared memory that exists in Java. Titanium semantics are consistent with Java semantics in the following sense: the operational semantics given in the Java Language Specification (Chapter 17) correctly implements the behavioral specification given below. We use the behavioral specification here for conciseness and to avoid constraints (or the appearance of constraints) on implementations.

As Titanium processes execute, they perform a sequence of actions on memory. In Java terminology, they may *use* the value of a variable or *assign* a new value to a variable. Given a variable V, we write *use*(V, A) for a use of V that produces value A and *assign*(V, A) for an assignment to V with value A. A Titanium program specifies a sequence of memory events, as described in the Java specification:

> [An implementation may perform] a *use* or *assign* by [thread] T of [variable] V ... only when dictated by execution by T of the Java program according to the standard Java execution model. For example, an occurrence of V as an operand of the + operator requires that a single *use* operation occur on V; an occurrence of V as the left-hand operand of the assignment operator (=) requires that a single *assign* operation occur.

Thus, a Titanium program defines a total order on memory events for each process/thread. This corresponds to the order that a naive compiler and processor would exhibit, i.e., without reorderings. The union of these process orders forms a partial order called the *program order*. We write $P(a, b)$ if event a happens before event b in the program order.

During an actual execution, some of the events visible in the Titanium source may be reordered, modified, or eliminated by the compiler or hardware. However, the processes see the events in some total order that is related to the program order. For each execution there exists a total order, E, of memory events from P such that:[1]:

1. $P(a, b) \Rightarrow E(a, b)$ if a and b access the same variable.
2. $P(l, a) \Rightarrow E(l, a)$, if l is a lock or barrier statement.
3. $P(a, u) \Rightarrow E(a, u)$, if u is an unlock or barrier statement.
4. $P(l_1, l_2) \Rightarrow E(l_1, l_2)$, if l_1 and l_2 are locks, unlocks, or barriers.
5. E is a correct serial execution, i.e.,
   (a) If $E(assign(V, A), use(V, B))$ and there is no intervening *write* to V, then $A = B$.
   (b) If there were n processes in P, then there are n consecutive barrier statements in E for each instance of a barrier.
   (c) A process T may contain an *unlock* operation l, only if the number of preceding *locks* by T (according to E) on the object locked by l is is strictly greater than the number of *unlocks* by T.
   (d) A process T may contain a *lock* operation l, only if the number of preceding *locks* by other processes (according to E) is equal to the number of preceding *unlocks*.
6. $P(a, b) \Rightarrow E(a, b)$ if a and b both operate on volatile variables.

Less formally, rule 1 says that dependences in the program will be observed. Rules 2 and 3 say that reads and writes performed in a critical demesne must appear to execute inside that demesne. Rule 4 says that synchronization operations must not be reordered. (Titanium extends the Java rules for synchronization, which include only lock and unlock statements to explicitly include barrier.) Rule 5 says that the usual semantics of memory and synchronization constructs are observed. Rule 6 says that operations on volatile variables must execute in order.

[1]See author's notes 1 and 2.

As in Java, the indivisible unit for assignment and use is a 32-bit value. In other words, the *assign* and *use* operations in the program order are on at most 32-bit quantities; assignment to double or long variables in Titanium source code corresponds to two separate operations in this semantics. Thus, a program with unsynchronized reads and writes of double or long values may observe undefined values from the reads[2]. It is a weakness of current implementation, unfortunately, that global pointers are not indivisible in this sense.

[2]See authors' note 3.

Chapter 10

Odds and Ends

Inlining. The `inline` qualifier on a method declaration acts as in C++. The semantics of calls to such methods is identical to that for ordinary methods. The qualifier is simply advice to the compiler. In particular, you should probably expect it to be ignored when the dynamic type of the target object in a method call cannot be uniquely determined at compilation time.

The qualifier may also be applied to loops:

```
foreach (p in Directions) inline {
    ...
}
```

This is intended to mean that the loop is to be unrolled completely. It is ignored if `Directions` is not manifest.

Chapter 11

Features Under Consideration

This section discusses features of Titanium whose implementation we have deferred indefinitely until we can evaluate the need for them.

11.1 Partition

The constructs

partition { C_0 `=>` S_0`;` C_1 `=>` S_1`;` `...;` C_{n-1} `=>` S_{n-1}`;` }

and

partition V { C_0 `=>` S_0`;` C_1 `=>` S_1`;` `...;` C_{n-1} `=>` S_{n-1}`;` }

divide a team into one or more teams without changing the total number of processes.

The construct begins and ends with implicit calls to `Ti.barrier()`. When all processes in a team reach the initial barrier, the system divides the team into n teams (some possibly empty). All those for which C_0 is true execute S_0. Of the remaining, all for which C_1 is true execute S_1, and so forth. All processes (including those satisfying none of the C_i) wait at the barrier at the end of the construct until all have reached the barrier.

Since the construct partitions the team, it also changes the value of `Ti.myTeam()`, (but not `Ti.thisProc()`) for all processes for the duration of the construct. If supplied, the variable name V is bound to an integer value such that `Ti.thisProc`$()$ = `Ti.myTeam`$()[V]$. Its scope is the text of all the S_i.

Chapter 12

Additions to the Standard Library

12.1 Grids

This syntax is not, of course, legal. We use it simply as a convenient notation. For each type T and positive integer n:

```
final class T [n d] {
  public static final int single arity = n;

  public RectDomain<n> single domain();

  public T [n d] single translate(Point<n> single p);
  public local T [n d] local single translate(Point<n> single p);

  public T [n d] single restrict(RectDomain<n> single d);
  public local T [n d] local single restrict(RectDomain<n> single d);

  public T [n d] single inject(Point<n> single p);
  public local T [n d] local single inject(Point<n> single p);

  public T [n d] single project(Point<n> single p);
  public local T [n d] local single project(Point<n> single p);

  public T [n d] single permute(Point<n> single p);
  public local T [n d] local single permute(Point<n> single p);

  // only if n > 1
  public T [(n - 1)d] single slice(int single k, int single j);
  public local T[(n - 1)d] local single slice(int single k, int single j);
```

```
      public void set(T value);

      public boolean isLocal ();
      public int creator ();
      public ti.lang.Region local regionOf ();
      public void noOverlap (TA B);
        /* Where TA is any grid type */

      public void copy(T [n d] x) overlap(this, x);

      public single void exchange(T myValue);

      public void readFrom(java.io.RandomAccessFile file)
         throws java.io.IOException;
      public void readFrom(java.io.DataInputStream str)
         throws java.io.IOException;
      public void writeTo(java.io.RandomAccessFile file)
         throws java.io.IOException;
      public void writeTo(java.io.DataOutputStream str)
         throws java.io.IOException;
    }
```

12.2 Points

```
template<int n> public immutable class Point {
      public static Point<n> single all(int single x);
      public static Point<n> single direction(int single k, int single x);
      public static Point<n> single direction(int single k);
      public Point<n> single op+(Point<n> single p);
      public Point<n> single op+=(Point<n> single p);
      public Point<n> single op-(Point<n> single p);
      public Point<n> single op-=(Point<n> single p);
      public Point<n> single op*(Point<n> single p);
      public Point<n> single op*=(Point<n> single p);
      public Point<n> single op/(Point<n> single p);
      public Point<n> single op/=(Point<n> single p);
      public Point<n> single op*(int single n);
      public Point<n> single op*=(int single n);
      public Point<n> single op/(int single n);
```

```
  public Point<n> single op/=(int single n);
  public boolean single op==(Point<n> single p);
  public boolean single op!=(Point<n> single p);
  public boolean single op<(Point<n> single p);
  public boolean single op<=(Point<n> single p);
  public boolean single op>(Point<n> single p);
  public boolean single op>=(Point<n> single p);
  public int single op[] (int single x);

  public static int single arity () { return n; }
  public Point<n> single permute (Point<n> single p);
}
```

12.3 Domains

```
template<int n> public immutable class Domain {
  public static final int single arity = n;

  // Domain set relationships
  public Domain<n> single op+(Domain<n> single d);
  public Domain<n> single op+=(Domain<n> single d);
  public Domain<n> single op-(Domain<n> single d);
  public Domain<n> single op-=(Domain<n> single d);
  public Domain<n> single op*(Domain<n> single d);
  public Domain<n> single op*=(Domain<n> single d);

  // Domain boolean relationships
  public boolean single op==(Domain<n> single d);
  public boolean single op!=(Domain<n> single d);
  public boolean single op<(Domain<n> single d);
  public boolean single op<=(Domain<n> single d);
  public boolean single op>(Domain<n> single d);
  public boolean single op>=(Domain<n> single d);

  // Point set relationships
  public Domain<n> single op+(Point<n> single p);
  public Domain<n> single op+=(Point<n> single p);
  public Domain<n> single op-(Point<n> single p);
  public Domain<n> single op-=(Point<n> single p);
```

```
  public Domain<n> single op*(Point<n> single p);
  public Domain<n> single op*=(Point<n> single p);
  public Domain<n> single op/(Point<n> single p);
  public Domain<n> single op/=(Point<n> single p);

  // Shape information
  public int single arity() { return n; }
  public Point<n> single lwb();
  public Point<n> single upb();
  public Point<n> single min();
  public Point<n> single max();
  public int single size();
  public boolean single contains(Point<n> single p);
  public RectDomain<n> single boundingBox();
  public boolean single isNull();
  public boolean single isRectangular();
}
```

12.4 RectDomains

```
template<int n> public immutable class RectDomain {
  public static final int single arity = n;
  public boolean isRectangular();

  public Domain<n> single op+(RectDomain<n> single d);
  public Domain<n> single op+=(RectDomain<n> single d);
  public Domain<n> single op-(RectDomain<n> single d);
  public Domain<n> single op-=(RectDomain<n> single d);
  public RectDomain<n> single op*(RectDomain<n> single d);
  public RectDomain<n> single op*=(RectDomain<n> single d);

  public RectDomain<n> single op+(Point<n> single p);
  public RectDomain<n> single op+=(Point<n> single p);
  public RectDomain<n> single op-(Point<n> single p);
  public RectDomain<n> single op-=(Point<n> single p);
  public RectDomain<n> single op*(Point<n> single p);
  public RectDomain<n> single op*=(Point<n> single p);
  public RectDomain<n> single op/(Point<n> single p);
  public RectDomain<n> single op/=(Point<n> single p);

  public boolean single op==(RectDomain<n> single d);
```

```
  public boolean single op!=(RectDomain<n> single d);
  public boolean single op<(RectDomain<n> single d);
  public boolean single op<=(RectDomain<n> single d);
  public boolean single op>(RectDomain<n> single d);
  public boolean single op>=(RectDomain<n> single d);

  public Domain<n> single op+(Domain<n> single d);
  public Domain<n> single op+=(Domain<n> single d);
  public Domain<n> single op-(Domain<n> single d);
  public Domain<n> single op-=(Domain<n> single d);
  public boolean single op==(Domain<n> single d);
  public boolean single op!=(Domain<n> single d);
  public boolean single op<(Domain<n> single d);
  public boolean single op<=(Domain<n> single d);
  public boolean single op>(Domain<n> single d);
  public boolean single op>=(Domain<n> single d);

  public final static int arity () { return n; }
  public Point<n> single lwb();
  public Point<n> single upb();
  public Point<n> single min();
  public Point<n> single max();
  public Point<n> single stride();
  public int single size();
  public boolean single isNull();
  public RectDomain<n> single accrete(int single k, int single dir,
                                      int single s);
  public RectDomain<n> single accrete(int single k, int single dir);
  public RectDomain<n> single accrete(int single k, Point<n> single S);
  public RectDomain<n> single accrete(int single k); // S = all(1)
  public RectDomain<n> single shrink(int single k, int single dir);
  public RectDomain<n> single shrink(int single k);
  public final Point<n> single permute (Point<n> single p);
  public RectDomain<n> single border(int single k, int single dir,
                                     int single shift);
  public RectDomain<n> single border(int single k, int single dir);
  public RectDomain<n> single border(int single dir);
  public boolean single contains(Point<n> single p);
  public RectDomain<n> single boundingBox();
  // only if n > 1
  public RectDomain<n - 1> single slice(int single k);
}
```

12.5 Reduction operators

Each process in a team must execute the same sequence of textual instances of calls on reduction operations, barriers, exchanges, and broadcasts.

```
package ti.lang;
class Reduce
{
  /* The result of Reduce.F (E) is the result of applying the binary
   * operator F to all processes' values of E in some unspecified
   * grouping.  The result of Reduce.F (E, k) is 0 or false for all
   * processes other than K, and the result of applying F to all the
   * values of E for processor K.
   *
   * Here, F can be 'add' (+), 'mult' (*),  'max' (maximum),
   * 'min' (minimum), 'and' (&), 'or' (|), or 'xor' (^).
   */

  public static single int add(int n, int single to);
  public static single long add(long n, int single to);
  public static single double add(double n, int single to);
  public static single int single add(int n);
  public static single long single add(long n);
  public static single double single add(double n);

  public static single int mult(int n, int single to);
  public static single long mult(long n, int single to);
  public static single double mult(double n, int single to);
  public static single int single mult(int n);
  public static single long single mult(long n);
  public static single double single mult(double n);

  public static single int max(int n, int single to);
  public static single long max(long n, int single to);
  public static single double max(double n, int single to);
  public static single int single max(int n);
  public static single long single max(long n);
  public static single double single max(double n);

  public static single int min(int n, int single to);
  public static single long min(long n, int single to);
  public static single double min(double n, int single to);
  public static single int single min(int n);
```

```
  public static single long single min(long n);
  public static single double single min(double n);

  public static single int or(int n, int single to);
  public static single long or(long n, int single to);
  public static single boolean or(boolean n, int single to);
  public static single int single or(int n);
  public static single long single or(long n);
  public static single boolean single or(boolean n);

  public static single int xor(int n, int single to);
  public static single long xor(long n, int single to);
  public static single boolean xor(boolean n, int single to);
  public static single int single xor(int n);
  public static single long single xor(long n);
  public static single boolean single xor(boolean n);

  public static single int and(int n, int single to);
  public static single long and(long n, int single to);
  public static single boolean and(boolean n, int single to);
  public static single int single and(int n);
  public static single long single and(long n);
  public static single boolean single and(boolean n);

  /* These reductions use OPER.eval as the binary operator, and are
   * otherwise like the reductions above. */

  public static single Object gen(ObjectOp oper, Object o, int single to);
  public static single Object gen(ObjectOp oper, Object o);

  public static single int gen(IntOp oper, int n, int single to);
  public static single int single gen(IntOp oper, int n);

  public static single long gen(LongOp op, long n, int single to);
  public static single long single gen(LongOp oper, long n);

  public static single double gen(DoubleOp oper, double n, int single to);
  public static single double single gen(DoubleOp oper, double n);
}


package ti.lang;
class Scan
```

```
{
  /* Scan.F (E) produces the result of applying the operation F to all
   * values of E for this and lower-numbered processes, according to
   * some unspecified grouping. */

  public static single int add(int n);
  public static single long add(long n);
  public static single double add(double n);

  public static single int mult(int n);
  public static single long mult(long n);
  public static single double mult(double n);

  public static single int max(int n);
  public static single long max(long n);
  public static single double max(double n);

  public static single int min(int n);
  public static single long min(long n);
  public static single double min(double n);

  public static single int or(int n);
  public static single long or(long n);
  public static single boolean or(boolean n);

  public static single int xor(int n);
  public static single long xor(long n);
  public static single boolean xor(boolean n);

  public static single int and(int n);
  public static single long and(long n);
  public static single boolean and(boolean n);

  /* As for the preceding scans, but with the operation F being
   * oper.eval. */
  public static single Object gen(ObjectOp oper, Object o);
  public static single int gen(IntOp oper, int n);
  public static single long gen(LongOp oper, long n);
  public static single double gen(DoubleOp oper, double n);
}
```

```
interface IntOp {
  int eval(int x, int y);
}

interface LongOp {
  long eval(long x, long y);
}

interface DoubleOp {
  double eval(double x, double y);
}

interface ObjectOp {
  Object eval(Object arg0, Object arg1);
}
```

12.6 Timer class

A Timer (type `ti.lang.Timer` provides a microsecond-granularity "stopwatch" that keeps track of the total time elapsed between start() and stop() method calls.

```
package ti.lang;
class Timer {

  /**  The maximum possible value of secs (). Roughly 1.84e13. */
  public final double MAX_SECS;

  /** Creates a new Timer object for which secs () is initially 0. */
  public Timer ();

  /** Cause THIS to begin counting. */
  public void start();

  /** Add the time elapsed from the last call to start() to the value
   *  of secs (). */
  public void stop();

  /** Set secs () to 0. */
  public void reset();
```

```
  /** The count of THIS in units of seconds, with a maximum
   *  granularity of one microsecond. */
  public double secs();

  /** The count of THIS in units of milliseconds, with a maximum
   *  granularity of one microsecond. */
  public double millis();

  /** The count of THIS in units of microseconds, with a maximum
   *  granularity of one microsecond. */
  public double micros();
}
```

12.7 Additional properties

The values of the following properties are available, as in ordinary Java, through calls to `java.lang.System.getProperty`.

runtime.distributed Has the value `"true"` if and only if the Titanium program reading it has been compiled for a platform with a distributed memory architecture, and otherwise `"false"`.

runtime.shared Has the value `"true"` iff some processes may share a memory space. (The CLUMP backends make "shared" and "distributed" orthogonal, rather than mutually exclusive.)

runtime.model Indicates the specific platform that the Titanium program reading it has been compiled for.

java.version, java.vm.version The `tc` (Titanium compiler) version.

runtime.boundschecking Has the value `"true"` if bounds checking is on.

runtime.gc Has the value `"true"` if garbage collection is on.

compiler.flags Flags passed to `tc` to compile the application.

12.8 java.lang.Object

As indicated in §6.1, all reference types implement the following, which may therefore be considered part of `java.lang.Object`:

- `r.creator()` returns the identity of the lowest-numbered process whose demesne contains the object pointed to by `r`. NullPointerException if `r` is null. This number may differ from the identity of the process that actually allocated the object when multiple processes share a demesne.
- `r.isLocal()` returns true iff `r` may be coerced to a local reference. This returns the same value as `r instanceof T local`, assuming `r` to have object type `T`. On some (but not all) platforms `r.isLocal()` is equivalent to `r.creator() == thisProc()`.
- `r.clone()` is as in Java, but with local references inside the object referenced by `r` set to null. The result is a global pointer to the newly created clone, which resides in the same region (see §6.3.2) as the object referenced by `r`. This operation may be overridden.
- `r.localClone()` is the default `clone()` function of Java (a shallow copy), except that `r` must be local. The result is local and in the same region (see §6.3.2) as the object referenced by `r`. See also §6.1.
- `r.regionOf ()` See §6.3.2.

12.9 java.lang.Math

The static methods in `java.lang.Math`, with the exception of `java.lang.Math.random`, take `single` arguments and produce `single` results.

12.10 Polling

The operation `Ti.poll()` services any outstanding network messages. This is needed in programs that have long, purely-local computations that can starve the NIC (e.g. a self-scheduled computation). It has no semantic content, and affects only performance (on some systems).

12.11 Sparse Titanium Array Copying

The `copy` method described in §4.2.1 applies to dense (rectangular) regions of grids specified by `RectDomains`. Here, we describe more general copying methods that take their index sets from general domains or from arrays of points.

The Titanium array operation `.copy()` takes an optional second parameter that can be a `Domain<`N`>` or a `Point<`N`> [1d]`, specifying the set of points to be copied (the types `Domain<`N`>` and `RectDomain<`N`>` have methods that make it easy to convert back and forth from `Point<`N`> [1d]`). For the purposes of modularity and performance, other sparse-array copying operations are divided into two lower-level components: a *gather* operation, which copies selected elements to contiguous points in an array, and its inverse, a *scatter* operation, which scatters values from a dense array using an index vector of points.

12.11.1 Copy

Assuming

```
T [N d] dest, src;
Domain<N> dom;
Point<N> [1d] pts;
```

the calls

```
dest.copy(src, dom)
dest.copy(src, pts);
```

copy the specified points from `src` to `dest`.

Restrictions.

- `pts` must not overlap `dest` or `src`.
- Each point element of `pts` or `dom` must be contained within the intersection of `dest.domain()` and `src.domain()` (it is a fatal error otherwise).
- If `T` is a non-atomic type, then it may not be the case that `src` resides in a private region and `dest` resides in a shared region.
- If `T` contains embedded local pointers then `src` and `dest` must both be local.
- The contents of `src` and `dest` may not be modified (i.e., by other processes) during the operation.

Effects. After the operation completes, the following conditions will hold:

- For every `Point<`N`>` p in `dom` (or in `pts`), `dest[`p`] == src'[`p`]` (where `src'` denotes the contents of `src` prior to the operation).
- All other values are unchanged.
- `pts` is permitted to contain duplicate points, but by definition these will not affect the result.
- `src` and `dest` are permitted to overlap, and if they do it will be as if the relevant values were first copied from `src` to an intermediate temporary array and then to `dest`.
- During the operation, the contents of `dest` at affected points is undefined.

12.11.2 Gather

Assuming

```
T [N d] src;
Point<N> [1d] pts;
T [1d] dest;
```

the call

```
src.gather(dest, pts);
```

packs the values from `src` selected by `pts` into `dest`, maintaining ordering of the points and data, and preserving any duplicated points in the packed array.

Restrictions.

- `dest.domain().size() >= pts.domain().size()` (i.e. there is enough space to gather into). It is a fatal error otherwise.
- Each point value in `pts` must be in `src.domain()`. It is a fatal error otherwise.
- None of the arrays may overlap.
- If `T` is a non-atomic type, then it may not be the case that `src` resides in a private region and `dest` resides in a shared region.
- If `T` contains embedded local pointers then `src` and `dest` must both be local.
- The contents of `src` and `pts` may not be modified (i.e., by other processes) during the operation.

Effects. After the operation completes, the following conditions will hold:

- `src` and `pts` will be unchanged
- For all i such that $0 \leq i <$ `pts.size()`,
  `dest[[`i`] + dest.min()] == src[pts[[`i`] + pts.min()]]`.
- The contents of `dest` are undefined while operation is in progress.
- `pts` is permitted to contain duplicate points. If it does, the corresponding `dest` elements will contain the relevant data values once for each duplicate (as implied by the description of the effects).

12.11.3 Scatter

Assuming

```
T [1d] src;
Point<N> [1d] pts;
T [N d] dest;
```

the call

```
dest.scatter(src, pts);
```

unpacks the values from `src` into `dest` at the positions selected by `pts`.

Restrictions.

- `pts.domain().size() <= src.domain().size()` (i.e. there are enough values to be scattered in `src`). It is a fatal error otherwise.
- Each point value in `pts` must be in `dest.domain()`. It is a fatal error otherwise.
- None of the arrays may overlap.
- If `T` is a non-atomic type, then it may not be the case that `src` resides in a private region and `dest` resides in a shared region.
- If `T` contains embedded local pointers then `src` and `dest` must both be local.
- The contents of `src` and `pts` may not be modified (i.e., by other processes) during the operation.

Effects. After the operation completes, the following conditions will hold:

- `src` and `pts` will be unchanged.
- For all i such that $0 \leq i <$ `pts.size()`,
  `dest[ptArray[[`i`] + ptArray.min()]] == src[[`i`] + destArray.min()]`.
- `ptArray` is permitted to contain duplicate points. If it does, the relevant `destArray` element will contain the data value corresponding to the highest-indexed duplicate in `ptArray`.
- The contents of `destArray` at the affected points are undefined while operation is in progress.

12.12 Bulk I/O

This library supports fast I/O operations on both Titanium arrays and Java arrays. These operations are synchronous (that is, they block the caller until the operation completes).

12.12.1 Bulk I/O for Titanium Arrays

Bulk I/O works through two methods on Titanium arrays: `.readFrom()` and `.writeTo()`. The arguments to the methods are various kinds of file—currently: `RandomAccessFile`, `DataInputStream`, `DataOutputStream`, in `java.io` and their subclasses `BulkRandomAccessFile`, `BulkDataInputStream`, and `BulkDataOutputStream` in `ti.io`.

Consider a Titanium array type whose elements are of an atomic type (§4.1). The methods following are defined for this type:

```
/** Perform a bulk read of data into the elements of this
 *  array from INFILE.  The number of elements read will be
 *  equal to domain().size().  They are read sequentially in
 *  row-major order.  Throws java.io.IOException in the
 *  case end-of-file or an I/O error occurs before all
 *  data are read. */
void readFrom (java.io.RandomAccessFile infile)
     throws java.io.IOException;
void readFrom (java.io.DataInputStream infile)
     throws java.io.IOException;
```

```
/** Perform a bulk write of data from the elements of this array
 *  to OUTFILE.  The number of elements written will be equal
 *  to domain().size().  They are written sequentially in row-major
 *  order. Throws java.io.IOException in the case of disk full or
 *  other I/O errors. */
void writeTo (java.io.RandomAccessFile outfile)
    throws java.io.IOException;
void writeTo(java.io.DataOutputStream outfile)
    throws java.io.IOException;
```

I/O on partial arrays. To read or write a proper subset of the elements in a Ti array, first use the regular array-selection methods such as `.slice()` and `.restrict()` to select the desired elements, then make I/O calls on the resultant arrays (these operations are implemented very efficiently without performing a copy).

12.12.2 Bulk I/O for Java Arrays in Titanium

The `BulkDataInputStream`, `BulkDataOutputStream`, and `BulkRandomAccessFile` classes in the `ti.io` package implement bulk, synchronous I/O. They subclass the three classes in `java.io` that can be used for I/O on binary data (so you can still use all the familiar methods), but they add a few new methods that allow I/O to be performed on entire arrays in a single call, leading to significantly less overhead (in practice speedups of over 60x have been observed for Titanium code that performs a single large I/O using the readArray() and writeArray() methods, rather than many calls to a single-value-at-a-time method like `DataInputStream.readDouble()`). These classes only handle single-dimensional Java arrays whose elements have atomic types (see §4.1).

```
package ti.io;

public interface BulkDataInput extends java.io.DataInput {
  /** Perform bulk input into A[OFFSET] .. A[OFFSET+COUNT-1] from this
   *  stream.  A must be a Java array with atomic element type.
   *  Requires that all k, OFFSET <= k < OFFSET+COUNT be valid indices
   *  of A, and COUNT>=0  (or throws ArrayIndexOutOfBoundsException).
   *  Throws IllegalArgumentException if A is not an array of appropriate
   *  type.  Throws java.io.IOException if end-of-file or input error
   *  occurs before all data are read. */
  void readArray(Object A, int offset, int count)
      throws java.io.IOException;
```

```
  /** Equivalent to readArray (A, 0, N), where N is the length of
   *  A. */
  void readArray(Object primjavaarray)
      throws java.io.IOException;
}
```

```
public interface BulkDataOutput extends java.io.DataOutput {
  /** Perform bulk output from A[OFFSET] .. A[OFFSET+COUNT-1] to this
   *  stream.  A must be a Java array with atomic element type.
   *  Requires that all k, OFFSET <= k < OFFSET+COUNT be valid indices
   *  of A, and COUNT>=0  (or throws ArrayIndexOutOfBoundsException).
   *  Throws IllegalArgumentException if A is not an array of appropriate
   *  type.  Throws java.io.IOException if disk full or other output
   *  error occurs before all data are read. */
  void writeArray(Object primjavaarray, int arrayoffset, int count)
      throws java.io.IOException;
  /** Equivalent to writeArray (A, 0, N), where N is the length of
   *  array A. */
  void writeArray(Object primjavaarray)
      throws java.io.IOException;
}
```

```
public class BulkDataInputStream
    extends java.io.DataInputStream
    implements BulkDataInput
{
  /** A new stream reading from IN.  See documentation of superclass. */
  public BulkDataInputStream(java.io.InputStream in);

  public void readArray(Object A, int offset, int count)
       throws java.io.IOException;

  public void readArray(Object A)
       throws java.io.IOException;
};
```

```
public class BulkDataOutputStream
    extends java.io.DataOutputStream
    implements BulkDataOutput
{
  /** An output stream writing to OUT. See superclass documentation. */
  public BulkDataOutputStream(java.io.OutputStream out);

  public void writeArray(Object A, int offset, int count)
      throws java.io.IOException;

  public void writeArray(Object A)
      throws java.io.IOException;
};


public class BulkRandomAccessFile
    extends java.io.RandomAccessFile
    implements BulkDataInput, BulkDataOutput
{
  /** A file providing access to the external file NAME in mode
   *  MODE, as described in the documentation of the superclass. */
  public BulkRandomAccessFile(String name, String mode)
      throws java.io.IOException;
  /** A file providing access to the external file FILE in mode
   *  MODE, as described in the documentation of the superclass. */
  public BulkRandomAccessFile(java.io.File file, String mode)
      throws java.io.IOException;

  public void readArray(Object A, int offset, int count)
       throws java.io.IOException;
  public void readArray(Object A)
       throws java.io.IOException;

  public void writeArray(Object A, int offset, int count)
       throws java.io.IOException;
  public void writeArray(Object primjavaarray)
       throws java.io.IOException;
};
```

Chapter 13

Various Known Departures from Java

Blank finals. Currently the compiler does not prevent one from assigning to a blank final field multiple times. This minor pathology is sufficiently unimportant that is unlikely to be fixed, but it is best for programmers to adhere to Java's rules.

Finalization. Currently finalization is not implemented.

Main procedure. There can only be one main function matching the required signature in the union of all the source files processed during a compilation.

Dynamic class loading. Titanium does not implement `java.lang.ClassLoader` or the `java.lang.Class.forName` method.

Thread creation. SPMD processes are the only threads that may be created. Java classes that depend on thread creation, such as those in `java.awt` and `java.net`, are consequently not implemented.

Chapter 14

Handling of Errors

Technically, in those places that the language specifically says that "it is an error" for the program to perform some action, the result of further execution of the program is undefined. However, as a practical matter, compilers should comply with the following constraints, absent a compelling (and documented) implementation consideration. In general, a situation that "is an error" should halt the program (preferably with a helpful traceback or other message that locates the error). It is not required that the program halt immediately, as long as it does so eventually, and before any change to state that persists after execution of the program (specifically, to external files). Therefore, it is entirely possible that several erroneous situations might be simultaneously pending, and such considerations as which of them to report to the user are entirely implementation dependent.

Erroneous exceptions. In addition to the erroneous conditions described in other sections of this manual, it is an error to perform any action that, according to the rules of standard Java, would cause the implementation to throw one of the following exceptions implicitly (that is, in the absence of an explicit 'throw' statement):

```
ArithmeticException  ArrayStoreException,
ClassCastException,
IndexOutOfBoundsException, NegativeArraySizeException,
NullPointerException,
ThreadDeath,
VirtualMachineError (and subclasses)
```

Appendix A

Planned Modifications

We currently intend to add the following features to vanilla Java:

- Foreign-function interfaces.
- A library of shared data types.
- A library class that provides the effect of "process static variables," that is variables that have one instance per process (as opposed to static variables, which have one instance per instance of the entire program).

In addition, we expect the following modifications to existing features:

- Remove the `Thread` and `ThreadGroup` classes and methods in other classes that produce them.
- Modifications to arithmetic engine.
- Different handling of exceptions in members of a process team.
- Explicit data-layout support.

Appendix B

Notes

These are collected discussion notes on various topics. This section is not part of the reference manual.

B.1 On Consistency

Note 1. We debated whether there should be a single total order E for a given execution or one for every process in the execution. The latter seems to admit cache implementations that are not strictly coherent, since processes may see writes happening in different orders. Our interpretation of the Java semantics is the stronger single serial order, so we have decided to use that in Titanium. This is subject to change if we find a significant performance advantage on some platform to the weaker semantics. Even with the single serial order, the semantics are quite weak, so it is unlikely that any program would rely on the difference. The following example is an execution that would be correct in the weaker semantics, but not in the stronger one – we are currently unable to find a motivating problem in which this execution would arise.

```
// initially X = Y = 0


        P1          P2              P3

        X = 2       X = Y           Y = X
        Y = 1

// Separating and labeling the accesses:

            P1          P2              P3
```

```
(A)     Write X     Read Y  (C)     Read X  (E)
(B)     Write Y     Write X (D)     Write Y (F)

// The following execution constitutes an incorrect behavior:

    Read Y (C) returns 1, Read X (E) returns 2,
    X = 2, Y = 1 at the end of execution.
```

We observe that:

- Access (C) consumes the value produced by (B) since it returns 1. The only other candidate is (F). Let us assume that (F) indeed wrote the value 1. That would imply:
  - (D) hasn't taken place yet
  - (E) read 1
  - (A) must have written 1, which is false.
- Similarly (E) consumes the value produced by (A).
- According to P2, since the final value of X is 2:

  ```
  B < C < D < A
  ```

- According to P3, since the final value of Y is 1:

  ```
  A < E < F < B
  ```

Note 2. The Titanium semantics as specified are weaker than Split-C's in that the default is weak consistency; sequential consistency (the default in Split-C) can be achieved through the use of volatile variables. However, this semantics is stronger than Split-C's *put* and *get* semantics, since Split-C does not require that dependences be observed. For example, a *put* followed by a *read* to the same variable is undefined in Split-C, unless there is an intervening *synch*. This stronger Titanium semantics is much nicer for the programmer, but may create a performance problem on some distributed memory platforms. In particular, if the network reorders messages between a single sender and receiver, which is likely if there are multiple paths through the networks, then two writes to the same variable can be reordered. On shared memory machines this will not be an issue. We felt that it was worth trying to satisfy dependences at some risk of performance degradation.

Note 3. The Java specification makes this qualification about divisibility only on non-volatile double and long values. It gives the (unstated) impression that accesses to 64-bit volatile values are indivisible. This seems to confuse two orthogonal issues: the size of an indivisible value and the relative order in which operations occur.

B.2 Advantages of Regions [David Gay]

- The memory management costs are more explicit than with garbage collection: there is a predictable cost at region creation and deletion and on each field write. The costs of the reference counting for local variables should be negligible (at least according to the study we did for our PLDI paper, but I am planning a somewhat different implementation). With garbage collection, pauses occur in unpredictable places and for unpredictable durations.
- Region-based memory management is safe.
- I believe that this style of region-based memory management is more efficient than parallel garbage collection. Obviously this claim requires validation.
- When reference-counting regions instead of individual objects two common problems with reference counting are ameliorated: minimal space is devoted to storing reference counts, and cyclic structures can be collected so long as they are allocated within a single region.

B.3 Disadvantages of Regions [David Gay]

- Regions are obviously harder to use than garbage-collection.
- As formulated above, regions will not mesh well with threads: you need to stop all threads when you wish to delete a shared region. Currently this is enforced by including a barrier in the shared region deletion operation - with threads this is no longer sufficient. There are a number of possible solutions, but none of them seem very good:
  - Require `r.delete()` to be called from all threads. This would be painful for the programmers.
  - The implementation of `r.delete()` can just stop the other threads on the same processor. However, to efficiently handle local variables containing references I need to know all points where a thread may be stopped (and obviously if these

points are “all points in the program” then efficiency is lost). So this solution doesn’t seem very good either.

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