The design of SecreC for Sharemind 3

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The virtual computer

- Stores a bunch of values. Each value has
  - a protection domain kind (PDK)
  - a data type
- Implements a bunch of protocols for various operations on data of various types in various PDKs
  - Each protocol / algorithm identified as a syscall
- Learns from its program, which syscalls to invoke on which data in which order

Features of the high-level language

- Imperative language (While) with procedures
- PDKs, protection domains (PD)
- Data structures (currently arrays only)
- Data types annotated with PDs
  - only atomic data
- **PD-polymorphism** for procedures
- Procedure overloading and specialization for particular PDKs
- Control flow is public

A basic code example

```
kind public;
domain public public;
kind additive3p;
domain private additive3p;
```

```
template<domain T1:additive3p>
  T1 int read_int() =
  "additive3p_read_int"
```

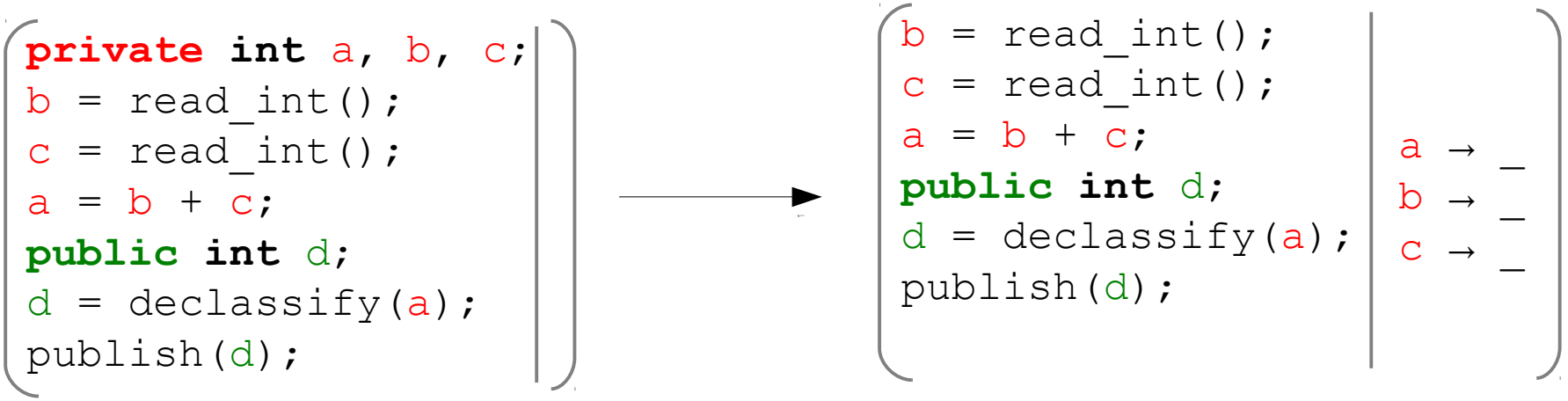
```
void main () {
  private int a, b, c;
  b = read_int();
  c = read_int();
  a = b + c;
  public int d;
  d = declassify(a);
  publish(d);
}
```

```
template<domain T1:additive3p>
  T1 int operator+(T1 int x, T1 int y) =
  "additive3p_add_ints"
```

```
template<domain pub:public>
  void publish(pub int x) =
  "print_int"
```

```
template<domain T1:additive3p, domain T2:public>
  T2 int declassify(T1 int x) =
  "declassify_additive3p_public_int"
```

Small-step semantics



```
template<domain T1:additive3p>
  T1 int read_int() =
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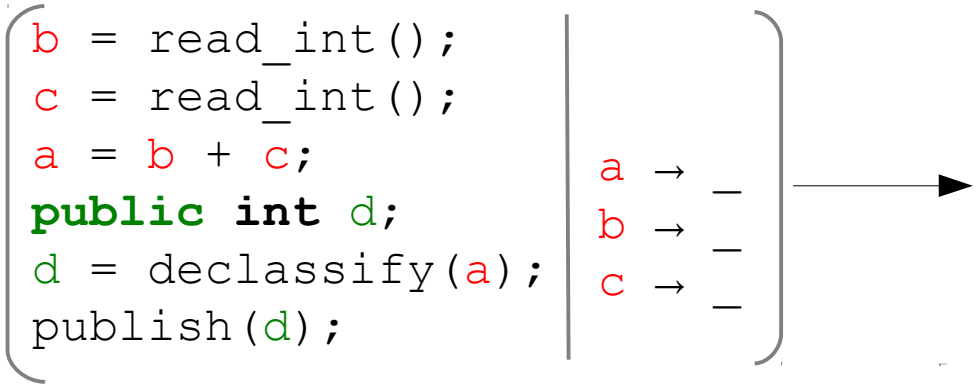
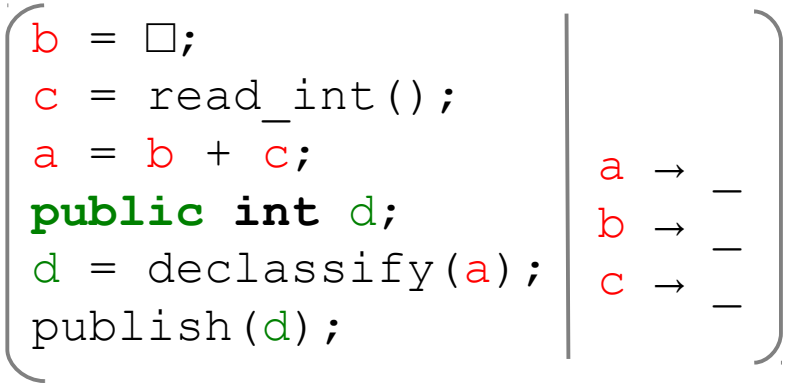
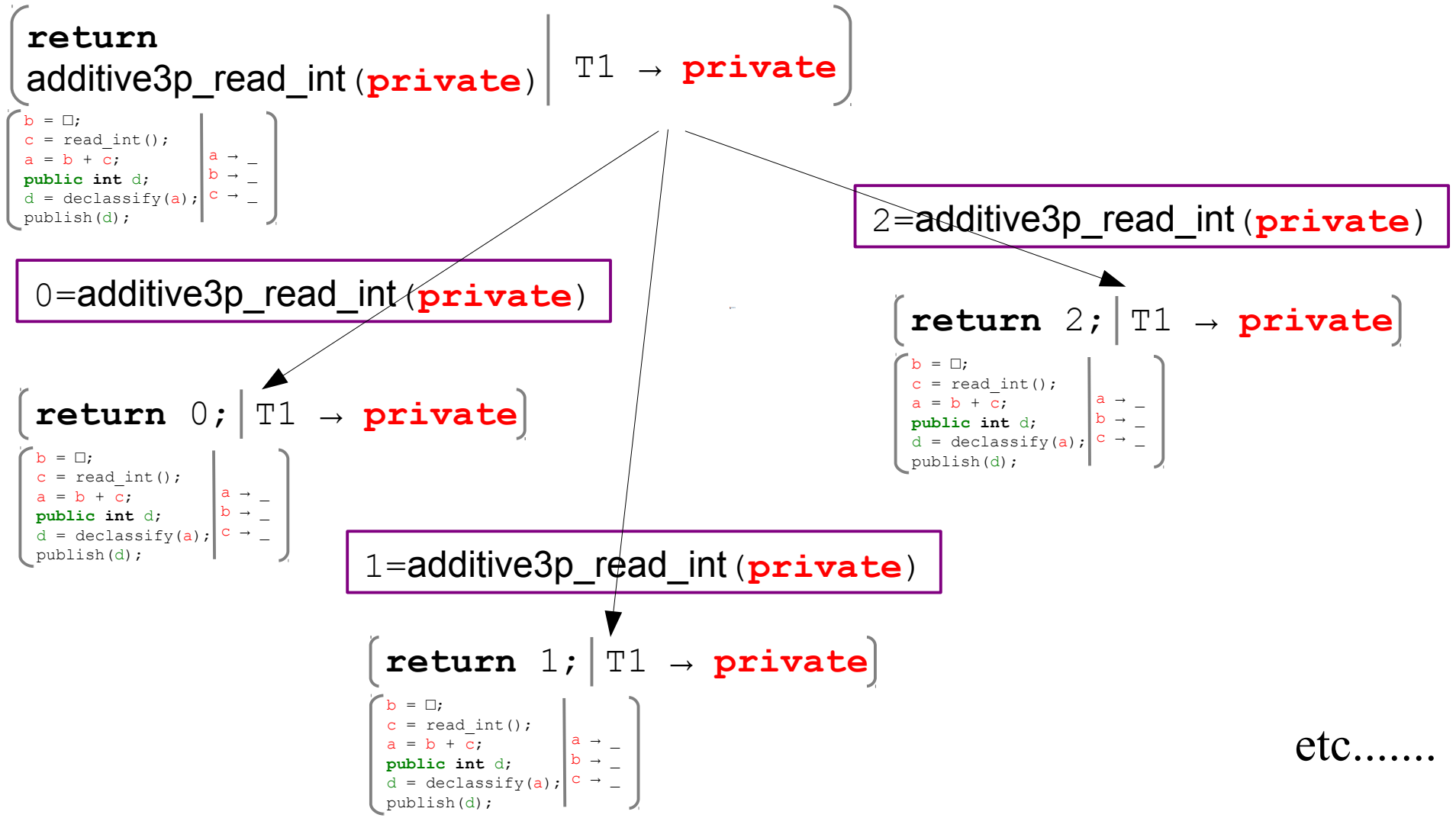
Small-step semantics

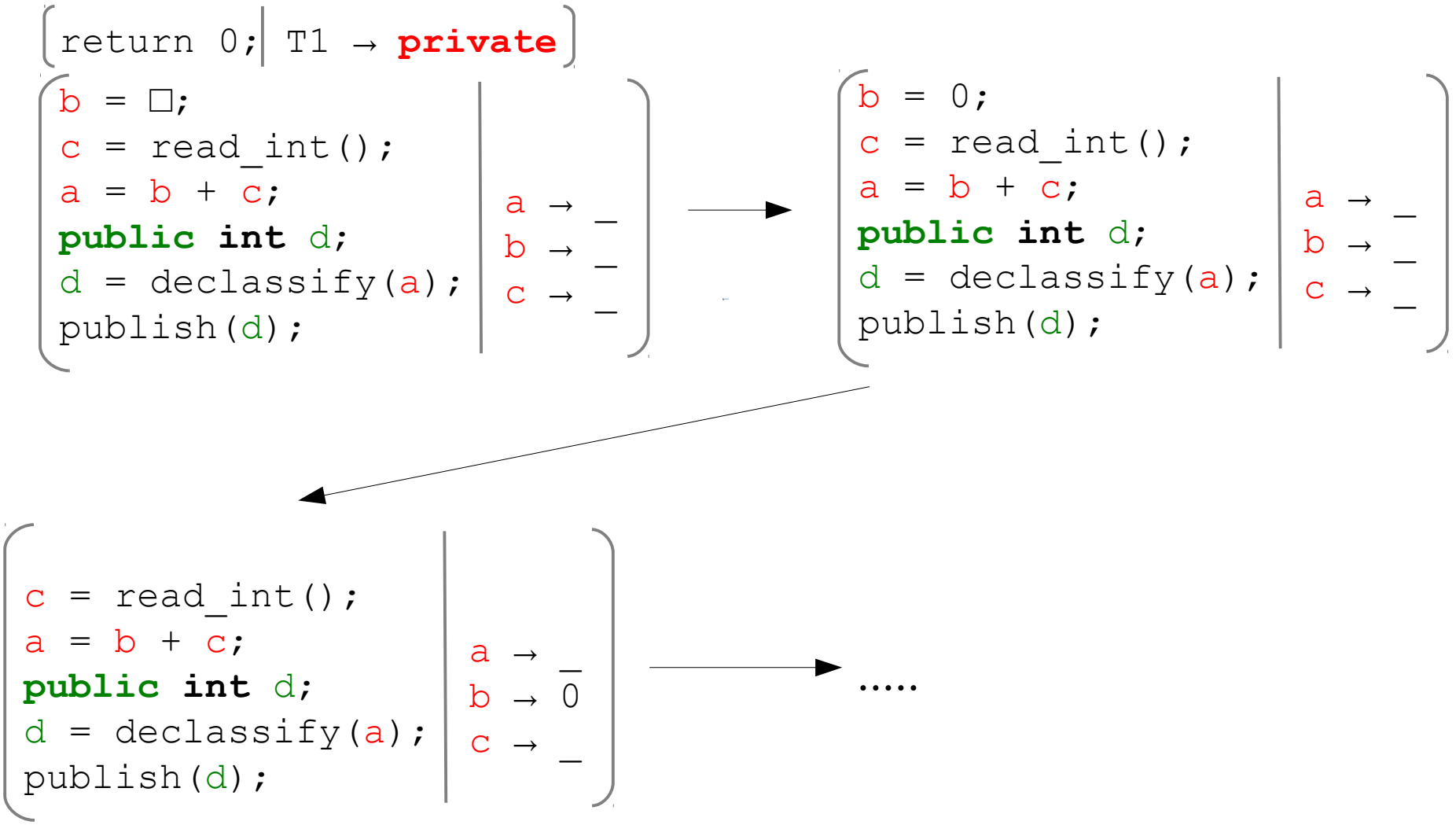




Small-step semantics



Small-step semantics



Feature: PD-polymorphism

```
template<domain T1, domain T2, domain T3>
T1 int [[1]] operator* (T2 int[[1]] x, T3 int[[1]] y) {
  T1 int [[1]] result (size(x));
  public int i;
  assert(size(x) == size(y));
  for (i = 0; i < size(x); i++) {
    result[i] = x[i] * y[i];
  }
  return result;
}
```

- In runtime, `T1,T2,T3` are instantiated with concrete protection domains
- These are used to locate the correct `T1 int operator*(T2 int, T3 int)`
- The success of locating is determined at compile-time

Feature: procedure overloading

```
template<domain T1:public>
T1 int operator*(T1 int x, T1 int y)= “public_mult”

template<domain T1:additive3p>
T1 int operator*(T1 int x, T1 int y)= “additive3p_mult_int”

template<domain T1:fhe>
T1 int operator*(T1 int x, T1 int y)= “fhe_mult_int”

template<domain T1:additive3p, domain T2:public>
T1 int operator*(T1 int x, T2 int y)=
“additive3p_mult_int_const”
```

Issues with overloading

```
template<domain T1:fhe, domain T2:fhe>
T1 int reclassify(T2 int x) = "fhe_reclassify_int"

template<domain T1>
T1 int reclassify(T1 int x) { return x; }
```

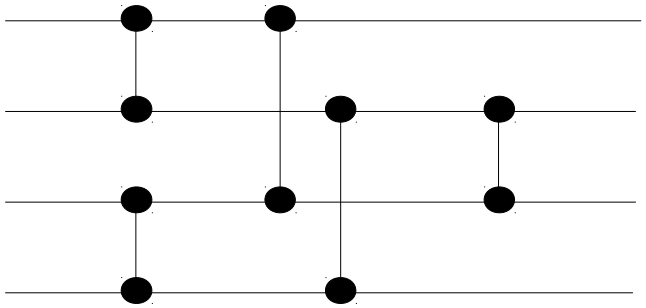
```
kind fhe;
domain private fhe;
.....
private int x, y;
.....
y = reclassify(x);
```

- Which `reclassify` should we call?
- We introduce priorities in an ad-hoc manner

Expected use of polymorphism in development

- For each PDK, a signature file associates arithmetic and other operations with syscalls
- Each PDK may have a different set of available operations
- A “standard library” provides low-priority implementations for most operations
- Most code is written PD-polymorphically
- Main program fixes PDKs of data
- Compiler checks that necessary operations are present in used PDKs

Example: sorting



- A comparator is c(x,y) = (min(x,y),max(x,y))
- c(x,y) ≡ **let** b = lt(x,y) **in** (x*b+y*(1-b),x*(1-b)+y*b)
  - Here lt(x,y)=1 if x<y; lt(x,y)=0 if x≥y
- Sorting networks are built from comparators
  - Performed comparisons are independent of starting order
- Best practical sorting networks have $O(n \log^2 n)$ comparators in $O(\log^2 n)$ rounds
- Let `sortnet(n)` output a description of a sorting network for `n` inputs

Generic sorting routine

```
template<domain PD>
PD int[[1]] sort(PD int[[1]] src) {
  public int alength, i;
  public int[[2]] sn;
  PD int x, y, b;

  alength = size(src);
  sn = sortnet(alength);
  for(i=0; i < size(sn[0]); i = i+1) {
    x = src[sn[i,0]];
    y = src[sn[i,1]];
    b = lt(x, y);
    src[sn[i,0]] = x*b + y*(1-b);
    src[sn[i,1]] = x*(1-b) + y*b;
  }
  return src;
}
```

Sorting in additive3p PDK

- additive3p has a particularly efficient shuffle
  - template<domain PD> PD int[[1]] shuffle(PD int[[1]] src) = “additive3p_shuffle_ints”
- In a shuffled array, comparison results are random
  - Hence it's OK to make them public
  - The control flow can then depend on them

Sorting routine for additive3p

```
template<domain PD:additive3p>
PD int[[1]] sort(PD int[[1]] src) {
  ... variable declarations ...

  src = shuffle(src);

  Sort src. For comparing positions a and b use
     declassify(lt(src[a],src[b]))

  return src;
}
```

- Quicksort can be done with O(n log n) work in O(log n) rounds.

Semantics

- Configuration: list of stack frames
- Stack frame: <program part, values of var.s>
- Labeled transition system over configurations
  - "most" transitions have empty labels
  - Only transitions corresponding to syscalls have non-empty labels
  - Syscall "f" with arguments $v_1,...,v_n$ in PDs $d_1,...,d_n$ returning a value in PD d_0 has a label

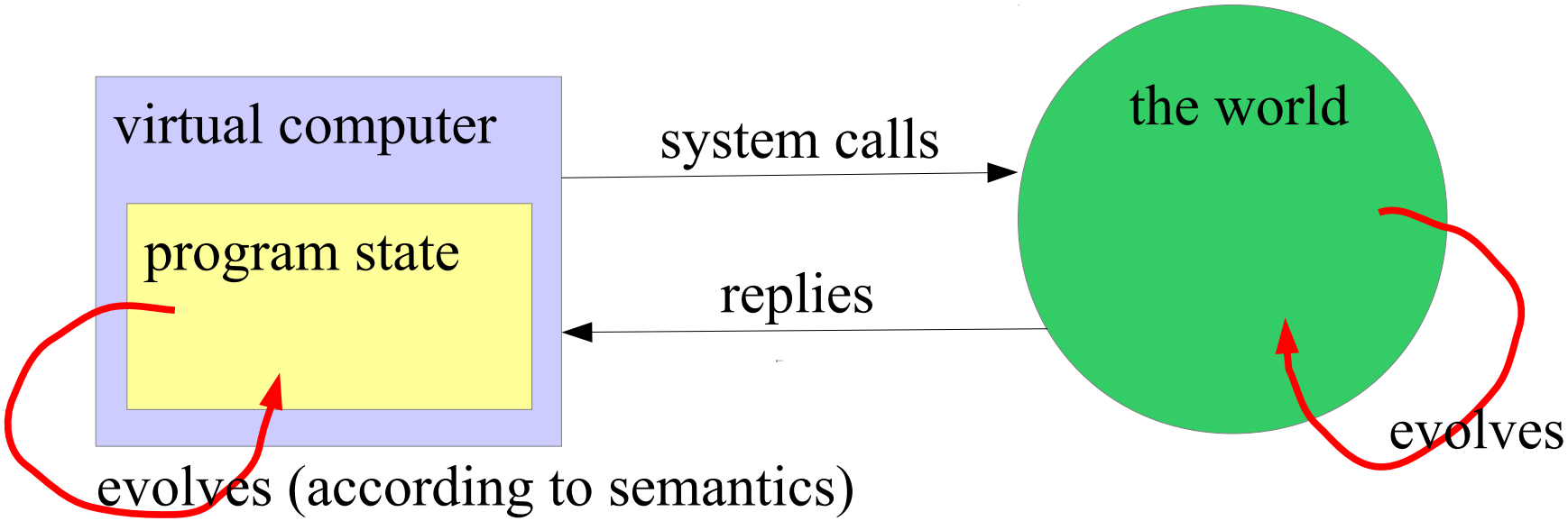
$$w = f(v_1,...,v_n,d_0,d_1,...,d_n)$$

  - w picked non-deterministically

Collecting syscalls

- The collecting semantics [[P]] of a program P is a set of sequences of labels
- Each sequence corresponds to a possible trace in the LTS given by the operational semantics of P
  - Empty labels are invisible in this sequence

Implementation of syscalls



$\mathcal{W}$ — set of all possible states of the world

the semantics of an n-ary syscall $f(v_1, \ldots, v_n; d_0, d_1, \ldots, d_n)$ has the type $[\![f]\!] : \mathbf{Val}^n \times \mathbf{PD}^{n+1} \times \mathcal{W} \to \mathbf{Val} \times \mathcal{W}$

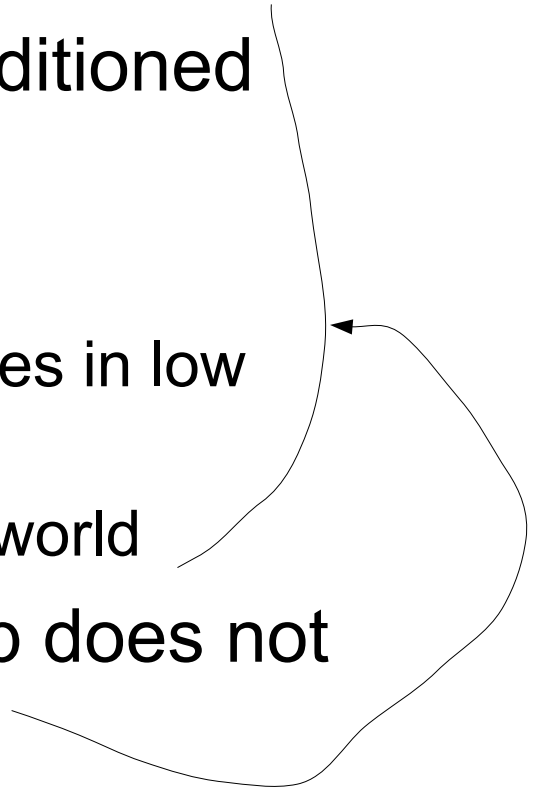
The evolution of the system is determined by the initial state of the world

Security of information flow

- Let $\mathfrak{PD}$ be partitioned to $\mathfrak{PD}_L$ [$\mathfrak{PD}_H$
- DW – distribution of the init. state of the world
  - $\mathcal{W} \cong \mathcal{W}_{\mathrm{L}} \times \mathcal{W}_{\mathrm{H}}$
  - DW keeps low and high component independent
- If $((w'_{\mathrm{L}}, w'_{\mathrm{H}}), v_0) = [\![f]\!](v_1, \ldots, v_n; d_0, \ldots, d_n; (w_{\mathrm{L}}, w_{\mathrm{H}}))$ then
  - w^0_L depends only on w_L and v_i, where $d_i 2 \mathfrak{PD}_L$
  - v_0 depends on w_H only if $d_0 2 \mathfrak{PD}_H$
- A syscall is declassifying if $d_0 2 \mathfrak{PD}_L$ and $d_i 2 \mathfrak{PD}_H$ for some i.

Security of information flow

- Let the program be running
- Consider the distribution DW_H conditioned over the *current* low-knowledge:
  - the program path
  - the current and past values of variables in low domains
  - the current and past low-state of the world
- **Theorem**. A non-declassifying step does not change the conditional distribution



Features of the intermediate language

- Imperative language (While) with procedures
- PDKs
- Data structures (currently arrays only)
- Data types annotated with PDKs
  - only atomic data
- Monomorphic procedures
- In syscalls: string constants instead of PDs
- **No interesting features really...**

Semantics of intermediate language

- SOS of While with procedures
- Syscalls are labeled and nondeterministic:

$$\texttt{syscall}(f; v_1, \ldots, v_n; d_0, \ldots, d_n) \xrightarrow{w=f(v_1,\ldots,v_n;d_0,\ldots,d_n)} w$$

  - w ranges over all possible values in the return type of f
  - d_i are strings here
- Other steps have empty labels
- We again get a set of sequences of labels
  - the world assigns a probability to each sequence

Translating from high-level to intermediate language

- variables / arguments of type `string` record the protection domains of variables / arguments / return values
- PDK-polymorphic functions are translated into several copies

Correctness of translation

- Semantics – set of sequences of labels
- This is preserved during translation

Preservation of security

- Secure information flow in terms of PDs cannot easily be defined for the intermediate language because there are no PDs
- **But:** our translation preserves the set of sequences of labels
- No world can distinguish a program from its translation
- In this sense, the noninterference properties are preserved