# *ParaScope:* Advanced Static Analysis for *ParaSail,* a Parallel Specification and Implementation Language

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## Where we are going

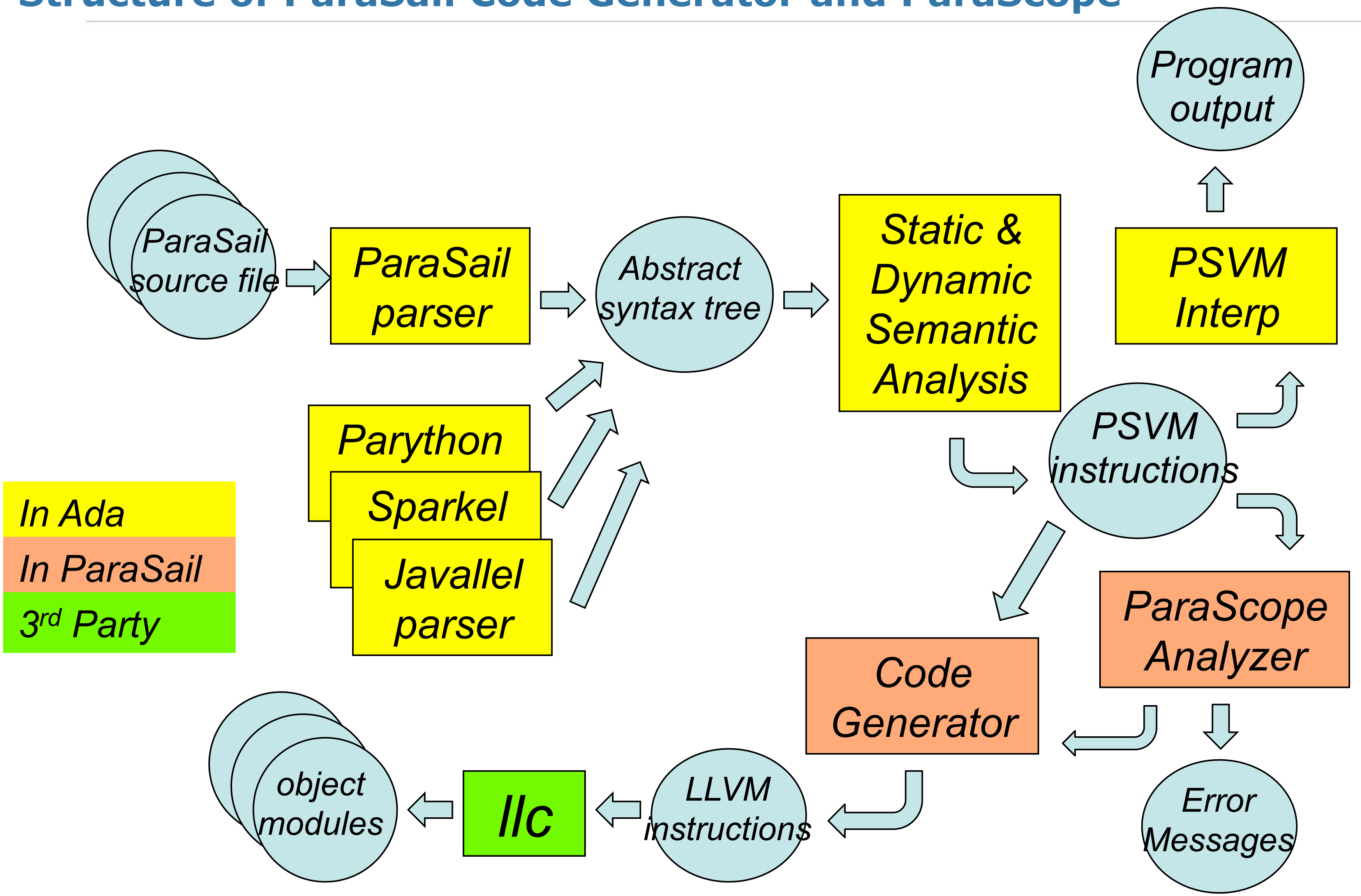
- **Background on ParaSail and ParaScope**
- **Conservative Data Race Detection**
- **Advanced Static Analysis:**
  - Abstract Interpretation and alternatives
- **Value-number approach to Abstract Interpretation in ParaScope Static Analyzer**
- **Inferring pre- and post- conditions in ParaScope**

# ParaSail and ParaScope

- ***ParaSail* – Parallel Specification and Implementation Language**
  - Pervasively Parallel Language, both implicit and explicit
  - Safety through Simplification:
    - No Global Variables
    - No Parameter Aliasing
    - No Re-Assignable Pointers
    - No Unstructured Locking or Signaling
  - Hoare-like syntax for explicit assertion/precondition/postcondition/invariant
  - Conservative Data Race Detection built into ParaSail front end

- ***ParaScope* – ParaSail Static Catcher of Programming Errors**
  - Re-engineered Abstract Interpretation Approach using Value Numbers
  - Integrated into LLVM-Based Code Generator
    - Immediate Feedback to Programmer about all possible Run-Time Errors
      - Identifies possible violations of assertions/preconditions/…
    - Feedback to Code Generator to optimize generated LLVM

## Structure of ParaSail Code Generator and ParaScope



# Conservative Data Race Detection in ParaSail front end

```
class Race_Cond is
  exports
    func Update_Both(var X : Integer;
                               var Y : Integer) is
      X := X + 1 || Y := Y - 1;
    end func Update_Both;
    func Update_One(var X : Integer;
                               Y : Integer) is
      X := X + 10;
    end func Update_One
    func Update_And_Return(var X : Integer)
      -> Integer is
      X := X + 100;
      return X - 50;
    end func Update_And_Return
    func Return_Ref(ref X : Integer)
      -> ref Integer is
      return X;
    end func Return_Ref;
end class Race_Cond;
```

```
 Race_Cond::Update_Both(A, B);

 Race_Cond::Update_Both(A, A);
** W/W Data Race on A ----- ^ - ^

 Race_Cond::Update_One(A, A);
** W/R Data Race on A ----- ^ - ^

 Race_Cond::Update_One(A, -A);
 A := Race_Cond::Update_And_Return(A);
 Race_Cond::Update_One
   (A, Race_Cond::Return_Ref(B));

 Race_Cond::Update_One
   (Race_Cond::Return_Ref(A), <-+
    Race_Cond::Return_Ref(A));   |
** W/R Data Race on A -------^ ----- +

 Race_Cond::Update_One
   (Race_Cond::Return_Ref(A),
    Race_Cond::Return_Ref(B));
```

## Data Race Detection handles up-level references

```
26    func dummy() is
27      var Up : I1 := create()
28      func B(I : I1);
29      func A() is
30        var X : I1 := create()
31        B(X)
32      end func A
33      func B(I : I1) is
34        read(I)
35        bump(Up)
36      end func B
37      func C() is
38        var Y : I1 := create()
39        B(Y)
40        read(Up)
41      end func C
42      func D() is
43        var Y : I1 := create()
44        B(Y)
45        B(Up)  //  Data Race with Up
            ^ -- Warning: W/R Data Race on Up
                           at mut_recurse.psl:35:15:
46      end func D
47      A()
48      C()
49      D()
50      block
51        A()
52      ||
53        C()  // Data races
            ^ -- Warning: W/W Data Race on Up
                           at mut_recurse.psl:51:9:
            ^ -- Warning: W/R Data Race on Up
                           at mut_recurse.psl:51:9:
54      end block
55    end func dummy
```

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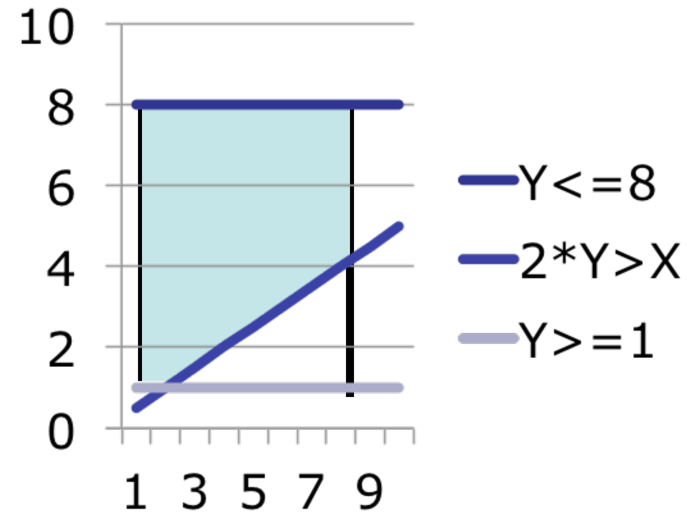
# *ParaScope:*

## Advanced Static Analysis based on Re-Engineered Abstract Interpretation

## What is Abstract Interpretation?

- **Approximates the set of possible states of all variables at each point in a program, to allow proofs for safety, security, or correctness.**
- **Iterates until a fixed-point, then checks for violations.**
- ***Constructs* the set of possible values, rather than *searching* through them (handles large ranges).**
- **Represents relationships, e.g. 2*Y > X, using, e.g. polygons/polyhedrons**

**X in 1..8, Y in 1..8, 2*Y > X:**



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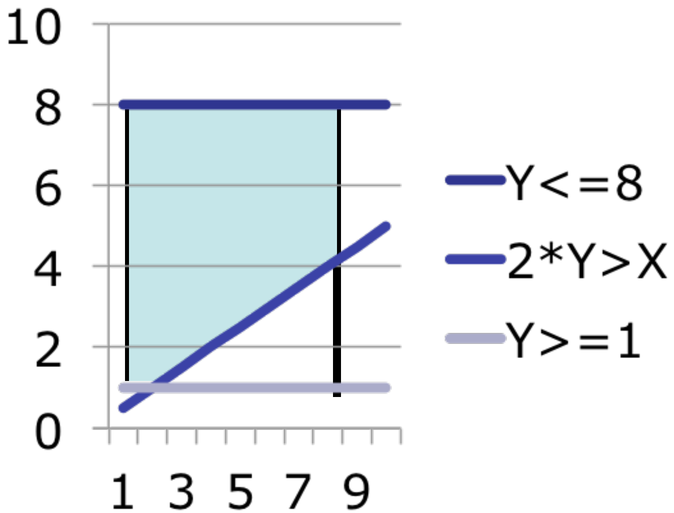
## Alternative Program Proof Techniques

- **Model Checking (e.g. SPIN model checker)**
  - Searches through state space for states that violate desirable properties
  - State explosion is a challenge; may limit loop iterations
  - Symbolic Model Checking can help
- **Formal Proof (e.g. SPARK 2014 toolset)**
  - Constructs a series of Verification Conditions (VCs) that represent desired safety, security, or correctness properties that should hold at various points in the program
  - Use SMT Solver or equivalent to prove each Verification Condition
  - Use timeout to determine VC cannot be proved
  - Typically relies on programmer to provide pre/postconditions, loop invariants, etc.

## What is the problem with "classic" Abstract Interpretation?

- **Polyhedral representation of relationships between variables is fundamentally limiting (e.g. Y > B – X*Z/A)**
- **Many approaches exist (courtesy of WikiPedia):**
  - congruence relations on integers
  - convex polyhedra (high computational costs)
  - "octagons"
  - difference-bound matrices
  - linear equalities
- **Other issues:**
  - Initial value set for inputs may require exploring all paths that reach procedure
  - May require a driver or harness to provide realistic input values



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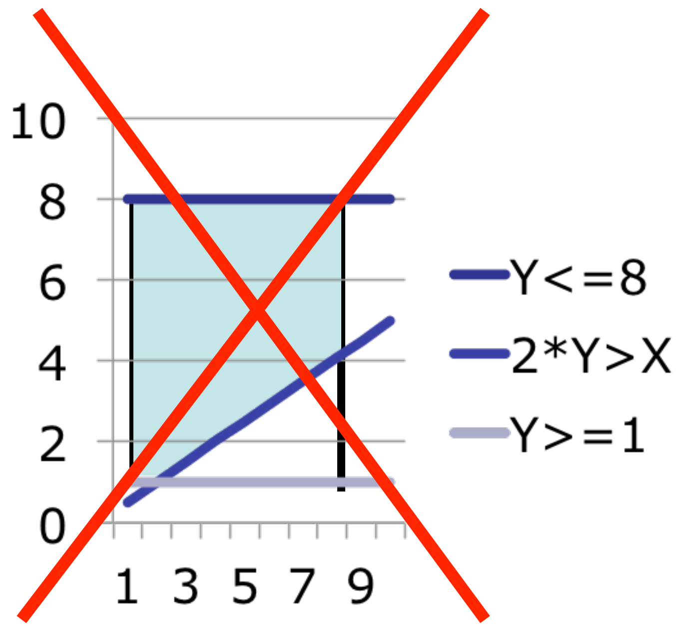

## Can we Re-Engineer Abstract Interpretation to solve this?

**Basic Trick used in ParaScope Static Analyzer:**

- **Trick first learned in 1982 from Bob Morgan for Ada compiler**
- **Use "Value Numbers" to represent value of computing *interesting* expressions (e.g. "Y * 2 – X")**
- **Associate Value Sets (Vsets) with Value Numbers (VNs)**
- **Unlike variables, value numbers don't *change* in value over time**
  - *but what we know about them does*
- **Value set "*shrinks*" when we do a conditional jump**
  - e.g. **if** Y*2 > X **then** …
    - in **then** part we know "Y*2-X" in 1 .. +inf
    - in **else** part we know "Y*2-X" in –inf .. 0
- **Also *shrinks* when we do a check or an assertion**
  - e.g. **assert** X + Y > Z ➔ "X+Y-Z" in 1 .. +inf

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## How do Value Numbers simplify value-set determination?

- **Only need to represent simple sets of integers, floats, or addresses for each value number (no polyhedrons!)**
- **Relationships between VNs are represented in value-number definition table (aka *computation table*)**
- **All variables/expressions with same value share a VN**
- **Each *basic block* and *edge* of Control Flow Graph (CFG) has its own *map* from VN to Value Set**
- **When one VN's Vset shrinks, we can efficiently *propagate* it to all related VNs in same map**

**Typical VN=>Vset Map:**

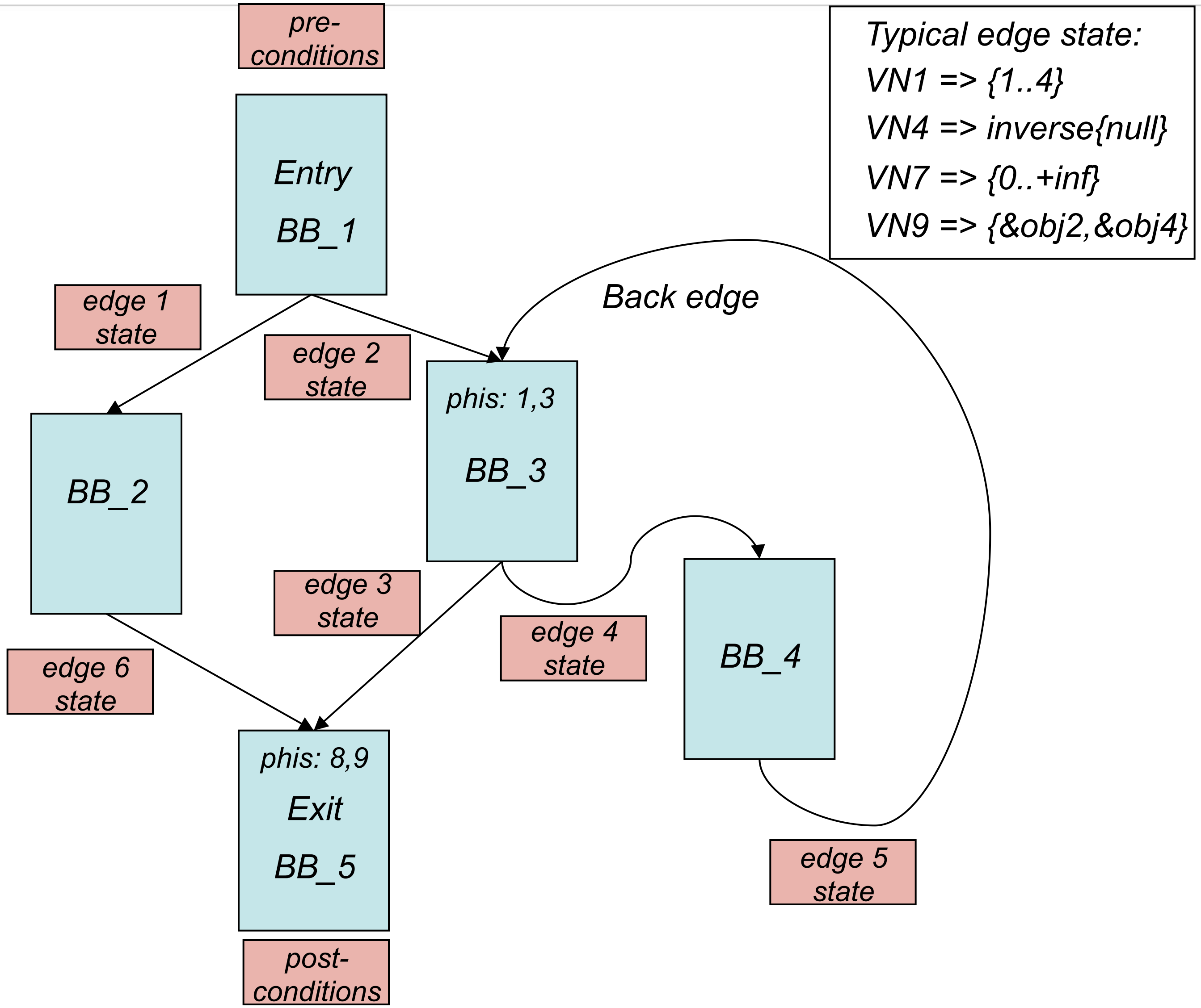
***VN1 => {1..4}***

***VN4 => inverse{null}***

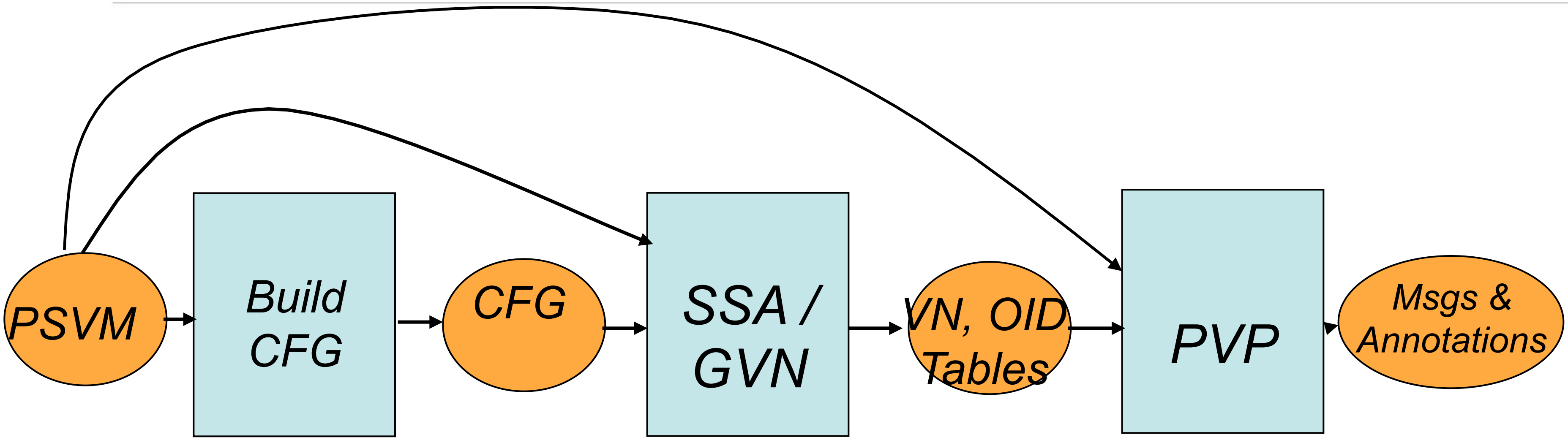
***VN7 => {0..+inf}***

***VN9 => {&obj2,&obj4}***

# Typical Control Flow Graph



# Overall 3-phase Structure of ParaScope Static Analyzer




*ParaScope Phase Responsibilities*

- CFG: *Identifies Basic Blocks and Builds (Sequentialized) CFG*
- SSA: *Converts into Single-Static-Assignment form*
- SSA: *Globally Assigns Origin IDs and Value Numbers*
- PVP: *Propagates Value Sets and Gives Warnings*

# Static Single Assignment/Global Value Numbering (SSA/GVN) phase

| Dominator Tree & Loop Identification | SSA Phi Placement | Global Value Numbering | VN Live Ranges |
|---|---|---|---|

- *Walk the "Control Flow Graph" of basic blocks and find loops, etc.*
- *Assign a unique "value number" to every fetch of a variable and every computation*
- *Use "phi" value numbers at join points to represent alternative values*
  - *E.g. if X > Y then Max := X else Max := Y end if; Max == ?  => PhiVN(X, Y)*
- *"Kappa" node introduced to represent value of potential alias after assignment*
  - *E.g. A[I] := 3; A[J] := 5; A[I] == ?  => KappaVN(I == J? 5: 3)*

## Goals of Possible Value Propagation (PVP) Phase

- **Compute Possible Value Set for every Value Number in every Basic Block**
  - Map of Value number to Value set
- **Check for failures of run-time checks, user assertions, and preconditions of called routines**
  - Initially assume checks will pass and thereby infer Pre/Postconditions
  - Iterate until a fixed point
  - Make final pass to report checks that still fail

*Typical VN=>Vset Map:*
*VN1 => {1..4}*
*VN4 => inverse{null}*
*VN7 => {0..+inf}*
*VN9 => {&obj2,&obj4}*

## PVP Iterative Cycle

- **Works one basic-block (BB) at a time.**
- **Initializes the "checks" table for each BB**
  - Summary of all "implicit" and "explicit" checks performed in BB for each VN
- **Applies checks of BB and then propagates changes in VN value sets until they stabilize**
  - Propagate "down" to constituent VNs, then "up" to composite VNs
  - e.g. VN1 = VN2 * VN3
    - Shrink VN1, propagate "down" to VN2 and VN3;
    - Shrink VN3, propagate "up" to VN1.
- **Computes VN state for each BB and for each outgoing edge**
  - Saves edge states for later iterations
  - Saves exit-block state for pre/postconditions

# Example of PVP warning messages

```
func Scope_Test
  (X : optional Integer;
  Y : optional Integer) -> Integer is
   var R : Countable_Range<Integer>
      := X .. Y
**       ^ --- ^ Operands might be null
   R := R.First + 2 .. R.Last + 2
   {R.Last - 2 == Y}
**                   ^ -- Assertion Might Fail §
   var L : List<Integer> :=
                 (Elem => 3, Next => null)
   const A := L.Elem
   L.Elem := L.Elem + 5
   const B := L.Elem + A
   L.Next := (Elem => B, Next => null)
   {L.Next.Elem == 11}
   {B == A + 6}
 **      ^ -- Assertion will fail here
   {B > X}
**     ^ -- Assertion might fail
```

```
if X is null then
** Edge 9 is dead; cannot reach here
      return 6
   elsif Y is null then
** Edge 12 is dead; cannot reach here
      {(X not null) == #true}
      return X
   else
      {X is null and Y is null}
**                    ^ -- Assertion will fail here
      if X > Y then
         {X - Y > 0}
         return X - Y
      else
         {X - Y <= 0}
         null
      end if
   end if
** Uninitialized function result here
end Scope_Test
```

§ *False Positive (associativity NYI)*

## Inferring Preconditions in PVP phase

- **Each Input** (parameter or global) **is given an "Input VN" to represent its** (unknown) ***initial*** **value**
- **Vset for Input VN is full possible range of type**
  - ***e.g.*** Inp_VN1 **in** $-2^{31}$ .. $+2^{31}-1$
- **As we apply checks and assertions Vset for Input VN may shrink, eliminating the "bad" values.**
- **VNs corresponding to combinations of Inputs and Literals** (e.g. Inp_VN1 – Inp_VN2 * 2) **might also undergo checks/assertions and might shrink** (directly or indirectly)
- **At exit block, Vset of Input VN or combination thereof represents the "*good*" values** (those that survived the checks and assertions)**, i.e. a *precondition***

***e.g.*** Inp1 – Inp2 * 2 **in** 1 .. +inf;     Inp2 **in** –inf .. -1 | +1 .. +inf

➔ ***Preconditions:*** Inp1 > Inp2 * 2;     Inp2 != 0

# Inferring Postconditions in PVP phase

**Same principle applies for Postconditions …**

- **In Exit Block, Vset associated with a VN that represents the final value of some Output** (parameter, global, or function result) **or combination thereof, represents possible values upon completion, i.e. a *postcondition***
- ***Example:***

```
proc Incr(X : in out Integer) is
     X := X + 1
end proc Incr
```

*initial value of X is Inp_VN1:* *Inp_VN1 in* $-2^{31}$ *..* $+2^{31}-1$

*final value of X is VN2 = Inp_VN1 + 1:* *VN2 in* $-2^{31}+1$ *..* $+2^{31}$

*check that X + 1 doesn't overflow:* *VN2 in* $-2^{31}+1$ *..* $+2^{31}-1$

*propagates to:* *Inp_VN1 in* $-2^{31}$ *..* $+2^{31}-2$

➔ *precondition: X'Initial <=* $2^{31}-2$

➔ *postcondition: X'Final in* $-2^{31}+1$ *..* $+2^{31}-1$*; X'Final = X'Initial+1*

# Screen shot showing Inferred Pre/Postconditions

```
P/P    --  Subp: fsw_example
       --
       --  Preconditions:
       --    N >= 1
       --
       --  Postconditions:
       --    A = One-of{1, 101, N - 1}
       --    A in (0..121 | 789..2^31-2)
       --    B = One-of{2, 102, N}
       --    B in (1..122 | 790..2^31-1)
       --    B = A + 1
       --
       --  Test Vectors:
       --    N: {123..456}, {457..789}, {1..122 | 790..2^31-1}
       --    A: {1}, {101}
       --    B: {2}, {102}
       --
      procedure Fsw_Example (N : Natural;
                             A, B : out Natural) is
      begin
       case N is
          when 123 .. 456 =>
             A := 1;
             B := 2;
          when 457 .. 789 =>
             A := 101;
             B := 102;
          when others =>
             A := N - 1;
             B := N;
       end case;
       pragma Assert (B - A = 1);
      end Fsw_Example;
```

## Summary

- **ParaSail Simplifies Conservative Data Race Detection**
  - Lack of Re-Assignable Pointers and Parameter Aliasing simplify problem
  - Can do checks at compile-time
  - Simplifies later static analysis
- **ParaScope Advanced Static Analysis Integrated with Compiler**
  - Uses Re-Engineered Abstract Interpretation based on Value Numbering
  - Assumes No data races are possible so can treat as sequential program
  - Gives immediate feedback to programmer about all possible run-time errors
- **Re-engineered value-number based approach in ParaScope:**
  - Can represent arbitrary relationships between variables
  - Uses efficient mechanism to propagate information between value numbers
  - Can infer both numeric and symbolic pre/postconditions so no need for drivers/harnesses or top-down walk