Bringing Static Analysis to the Masses:

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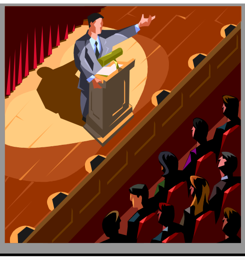

Outline of Presentation

- Why aren’t the masses using static analysis yet?
- What can we do about it?
- Integration into the development process
  - Integration into the IDE
  - Integration into the build process
  - Integration into the compiler
  - Integration into the language
- The design of ParaSail
  - *Parallel Specification and Implementation Language*

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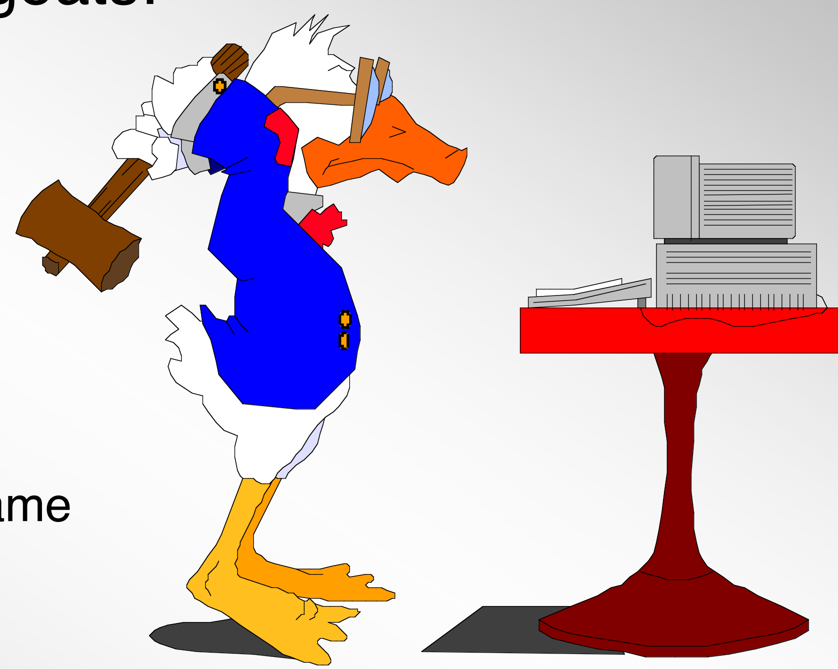
Why aren't the Masses using Static Analysis yet?

- This very question asked 10 days ago on Linked-In Static Code Analysis Group (by Steve Heffner)
- Many answers, many scapegoats:
  - Blame the customers?
    - Organizational laziness
    - Insecure programmers
  - Blame the marketers?
    - Early versions oversold
    - Current versions undersold
    - "Static Analysis" is a boring name
  - Blame the tools?
    - Too slow
    - Too much noise
    - Difficult to incorporate into build process
  - Blame the President?! (it is an election year after all)



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What can we do about it?

- Make static analysis an integral part of the development process rather than after-the-fact

- Provide “One Button” ease of use
- Run at a speed comparable to rest of build
  - Incremental analysis
  - Provide multiple depths of analysis
    - Similar to compiler optimization levels

- Provide success/failure indicator which can determine overall success/failure of build
  - Analogous to gcc’s “warnings are errors” (-Werror)
  - False positives must be easy enough to accommodate by suppressing or making a benign change
  - Get tools to agree on what is/is not a problem

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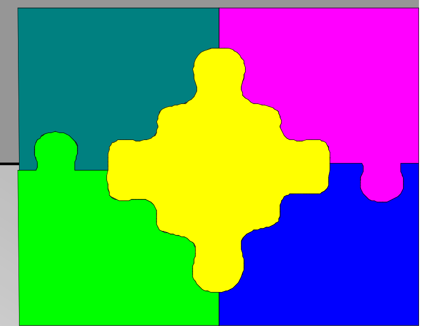
Levels of Integration



- Integration into the IDE
  - IDE plugin architecture should make this easier
  - e.g. Eclipse panel combines compiler and analyzer messages
  - Just check one box, or click on one menu item to produce static analysis results

- Integration into the Compiler/Linker
  - Use compiler's front end
  - Avoids front end incompatibilities and quirks
  - No need for separate configuration for target, subdirectories, libraries, etc.
  - Examples: Green Hills *DoubleCheck* and AdaCore *CodePeer*
  - Static analysis can then be seen as *Enhanced Compile-Time Checking* -- less threatening?

Ultimate Step: Integration Into the Language

- Eiffel helped to popularize notion of integrating annotations with language
- SPARK is example of this based on Ada
- JML and standard annotations like @notnull do this for Java
- But... These still rely on run-time checks and/or on separate tools -- we want *compile-time* checking.
- Can we require *compile-time* enforcement of *all* user annotations and *all* language-defined checks (e.g. array indexing, null pointer, etc.) as part of the language definition?
  - Java sticks “toe” in the water with initialization of local variables

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Is It Time to Design a Language for Safe and Secure Parallel Programming?

- What is New?
  - Hardware is no longer getting any faster
    - It is getting more parallel, and hence more difficult to program safely
  - Safety and Security is now everyone's concern
    - Everything is networked
  - Deep and Precise Static Analysis is coming of age
    - We can do sophisticated things in the compiler/linker
- What is True?
  - 80+% of safety-critical systems are developed in C and C++, two of the least safe languages invented in the last 40 years
  - In 10 years, many chips will have 64+ cores
  - Software has become the focus of more and more investment in almost all industries (e.g. 40% of R&D for automobiles)

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Designing A New Language

- **ParaSail** -- *Parallel Specification and Implementation Language*
- Designed to make parallel programming safe and convenient
- All checking is done at compile-time
  - No run-time checking, no run-time exceptions
  - No race conditions
  - User-definable safety and security constraints
- Heavy duty static analysis done by the compiler
  - Program fails to compile if compiler can't prove assertions

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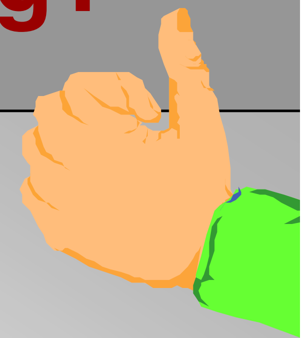
What makes ParaSail Interesting?



- Pervasive (implicit and explicit) parallelism
- Inherently safe:
  - preconditions, postconditions, constraints, etc., integrated throughout the syntax
  - no global variables; no dangling references
  - no run-time checks -- all checking at compile-time
  - no run-time exceptions
- Small number of flexible concepts:
  - Modules, Types, Objects, Operations
- User-defined literals, indexing, aggregates, physical units checking
- It's hot off the presses

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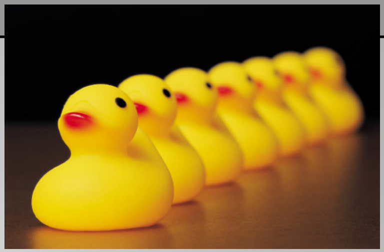
Parallelism in ParaSail



- Parallel by default
  - parameters are evaluated in parallel
  - have to work harder to make code run sequentially
- Easy to create even more parallelism
  - Process(X) || Process(Y) || Process(Z);
- Lock-based and lock-free concurrent objects
  - Lock-based objects also support queued access
  - User-defined delay and timed call based on queued access
- No global variables
  - Can only access or update variable state via parameters
- Compiler prevents aliasing and unsafe access to non-concurrent variables

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Examples of ParaSail Parallelism

```
Z := F(U) + G(V);    // F(U) and G(V) eval'ed in parallel
Process(A) || Process(B) || Process(C);  // All 3 in parallel

for X => Root then X.Left || X.Right while X not null
  concurrent loop
    Process(X);          // Process called on each node in parallel
end loop;

concurrent interface Box<Element is Assignable<>> is
    function Create() -> Box;  // Creates an empty box
    procedure Put(M : locked var Box; E : Element);
    function Get(M : queued var Box) -> Element; // May wait
    function Get_Now(M : locked const Box) -> optional Element;
end interface Box;

type Item_Box is Box<Item>;
var My_Box : Item_Box := Create();
```

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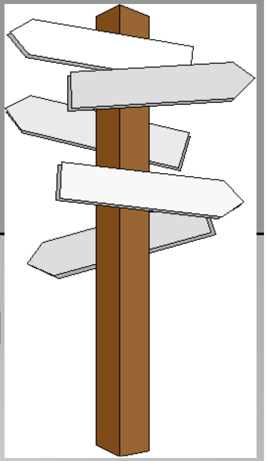
Annotations in ParaSail



- Preconditions, Postconditions, Constraints, etc. all u… same Hoare-like syntax: {X != 0}
- All assertions are checked at compile-time
  - no run-time checks inserted
  - no run-time exceptions to worry about
- Location of assertion determines whether is a:
  - precondition (before “->”)
  - postcondition (after “->”)
  - assertion (between statements)
  - constraint (in type definition)

Examples of ParaSail Annotations

```
interface Stack <Component is Assignable<>; Size_Type is Integer<>> is

    function Max_Stack_Size(S : Stack) -> Size_Type {Max_Stack_Size > 0};

    function Count(S : Stack) -> Size_Type
      {Count <= Max_Stack_Size(S)};

    function Create(Max : Size_Type {Max > 0}) -> Stack
      {Max_Stack_Size(Create) == Max and Count(Create) == 0};

    function Is_Empty(S : Stack) -> Boolean
      {Is_Empty == (Count(S) == 0)};

    function Is_Full(S : Stack) -> Boolean
      {Is_Full == (Count(S) == Max_Stack_Size(S))};

    procedure Push(S : ref var Stack {not Is_Full(S)}; X : Component)
      {Count(S') == Count(S) + 1};

    function Top(S : Stack {not Is_Empty(S)}) -> Component;

    procedure Pop(S : ref var Stack {not Is_Empty(S)})
      {Count(S') == Count(S) - 1};

end interface Stack;
```

More Annotation Examples

```
type Age is new Integer<0 .. 200>;
type Youth is Age {Youth <= 20};
type Senior is Age {Senior >= 50};
----------------------------------
function GCD(X, Y : Integer {X > 0 and Y > 0}) -> Integer
   {GCD > 0 and GCD <= X and GCD <= Y and
    X mod GCD == 0 and Y mod GCD == 0} is
  var Result := X;      {Result > 0 and X mod Result == 0}
  var Next := Y mod X; {Next <= Y and Y - Next mod Result == 0}

  while Next != 0 loop
    {Next > 0 and Next < Result and Result <= X}
    const Old_Result := Result;
    Result := Next; {Result < Old_Result}
    Next := Old_Result mod Result;
    {Result > 0 and Result <= Y and Old_Result - Next mod Result == 0}
  end loop;

  return Result;
end function GCD;
```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Overall ParaSail Model

- ParaSail has four basic concepts:
  - Module
    - has an Interface, and Classes that implement it
    - **interface** M <Formal **is** Int<>> **is ...**
  - Type
    - is an instance of a Module
    - **type** T **is** M <Actual>;
  - Object
    - is an instance of a Type
    - **var** Obj : T := T::Create(...);
  - Operation
    - is defined in a Module, and
    - operates on one or more Objects of specified Types.

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User-defined Indexing, Literals, etc.

- User-defined indexing
  - Any type with **operator** “[]” defined
  - Indexing function returns **ref** to component of parameter
- User-defined literals
  - Any type with **operator** “from_univ” defined from:
    - Univ_Integer (42), Univ_Real (3.141592653589793)
    - Univ_String (“Hitchhiker’s Guide”), Univ_Character (‘π’)
    - Univ_Enumeration (#red)
- User-defined ordering
  - Define single binary **operator** “=?” (pronounced “*compare*”)
  - Returns #less, #equal, #greater, #unordered
  - Implies “<=“, “<“, “==“, “!=“, “>”, “>=“, “in X..Y”, “not in X..Y”

More Examples of ParaSail

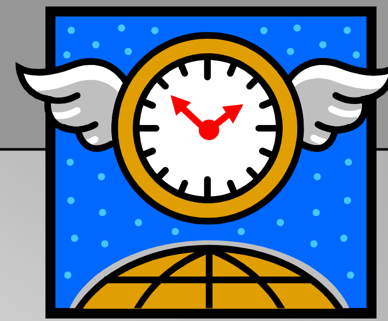
```
concurrent class Box <Element is Assignable<>> is
    var Content : optional mutable Element; // starts null and can change size
  exports
    function Create() -> Box is  // Creates an empty box
      return (Content => null);
    end function Create;

    procedure Put(M : locked var Box; E : Element) is
      M.Content := E;
    end procedure Put;

    function Get(M : queued var Box) -> Element // May wait
        queued until Content not null is
      const Result := M.Content;
      M.Content := null;
      return Result;
    end function Get;

    function Get_Now(M : locked const Box) -> optional Element is
      return M.Content;
    end function Get_Now;
end class Box;
```

Clock Example



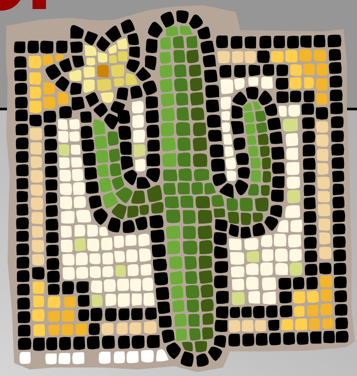
```
abstract concurrent interface Clock <Time_Type is Ordered<>> is
  function Now(C : Clock) -> Time_Type;
  procedure Delay_Until(C : queued Clock; Wakeup : Time_Type)
    {Now(C') >= Wakeup};  // queued until Now(C) >= Wakeup
end interface Clock;

concurrent interface Real_Time_Clock<...> extends Clock<...> is
  function Create(...) -> Real_Time_Clock;
  ...
end interface Real_Time_Clock;

var My_Clock : Real_Time_Clock <...> := Create(...);
const Too_Late := Now(My_Clock) + Max_Wait;

select  // multi-way parallel queued call
     const Data := Get(My_Box) => Process(Data);
  || Delay_Until(My_Clock, Wakeup => Too_Late) =>
          Put_Line(Out_Stream, "My_Box not filled in time");
end select;
```

Walk Parse Tree in Parallel



```
type Node_Kind is Enum < [#leaf, #unary, #binary] >;
  ...
for X => Root while X not null loop
  case X.Kind of
    #leaf =>
      Process_Leaf(X);
    #unary =>
      Process_Unary(X) ||
      continue loop with X => X.Operand;
    #binary =>
      Process_Binary(X) ||
      continue loop with X => X.Left ||
      continue loop with X => X.Right;
  end case;
end loop;
```

Parallel N-Queens Solution

```
interface N_Queens <N : Univ_Integer := 8> is
    // Place N queens on an NxN checkerboard so that none of them can
    // "take" each other.  Return vector of solutions, each solution being
    // an array of columns indexed by row indicating placement of queens.

  type Chess_Unit is new Integer<-N*2 .. N*2>;
  type Row is Chess_Unit {Row in 1..N};
  type Column is Chess_Unit {Column in 1..N};
  type Solution is Array<optional Column, Indexed_By => Row>;

  function Place_Queens() -> Vector<Solution>
   {for all S of Place_Queens: for all C of S: C not null};
end interface N_Queens;
```

Parallel N-Queens Solution
(cont'd)

```
class N_Queens is
    type Sum_Range is Chess_Unit {Sum_Range in 2..2*N};
    type Diff_Range is Chess_Unit {Diff_Range in (1-N) .. (N-1)};
    type Sum is Set<Sum_Range>;
    type Diff is Set<Diff_Range>;
  exports
    function Place_Queens() -> Vector<Solution>
     {for all S of Place_Queens: for all C of S: C not null}
    is
      var Solutions : concurrent Vector<Solution> := [];
     *Outer_Loop*
      for (C : Column := 1; Trial : Solution := [.. => null];
        Diag_Sum : Sum := []; Diag_Diff : Diff := []) loop
           // Iterate over the columns
           ...
           Solutions |= Trial;
           ...
      end loop Outer_Loop;
      return Solutions;
    end function Place_Queens;
end class N_Queens;
```

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Parallel N-Queens Solution *(cont'd)*

```
function Place_Queens() -> Vector<Solution> is
  var Solutions : concurrent Vector<Solution> := [];
 *Outer_Loop*
  for (C : Column := 1; Trial : Solution := [.. => null];
    Diag_Sum : Sum := []; Diag_Diff : Diff := []) loop // over the columns
    for R in Row concurrent loop                        // over the rows
      if Trial[R] is null and then
       (R+C) not in Diag_Sum and then (R-C) not in Diag_Diff then
        // Found a Row/Column combination that is not on any diagonal
        if C < N then          // Keep going since haven't reached Nth column.
          continue loop Outer_Loop with (C => C+1,
            Trial     => Trial | [R => C],
            Diag_Sum  => Diag_Sum  | (R+C),
            Diag_Diff => Diag_Diff | (R-C));
        else                   // All done, remember trial result.
          Solutions |= Trial;
        end if;
      end if;
    end loop;
  end loop Outer_Loop;
  return Solutions;
end function Place_Queens;
```

How does ParaSail Compare to ...

- C/C++ -- built-in safety; built-in parallelism
- Ada -- eliminates race conditions, increases parallelism, eliminates run-time checks, simplifies language
- Java -- eliminates race conditions, increases parallelism, avoids garbage collection, no run-time exceptions, compile-time checks against security constraints

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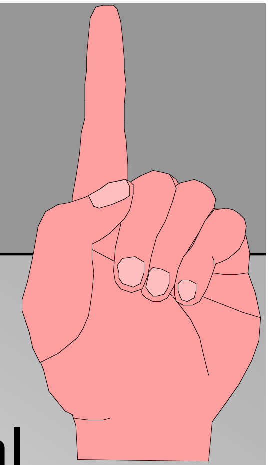
Some of the Open Issues in ParaSail

- If we eliminate pointers, what about “references”?
  - if references, when and where?
- If no global variables, how best to provide access to global “singleton” objects from environment
  - such as “the” database or “the” user or “the” filesystem
  - “Context” object with singletons as components passed to main subprogram?
- How to standardize how “smart” compiler is at proving assertions
  - Open source algorithm?
  - Detailed specification of inference and simplification rules?

Ultimate Test: Physical Units Example

```
interface Float_With_Units
  <Base is Float<>; Name : Univ_String; Short_Hand : Univ_String;
   Unit_Dimensions : Array <Element_Type => Univ_Real,
     Index_Type => Dimension_Enum> := [.. => 0.0]; Scale : Univ_Real> is

    operator "from_univ"(Value : Univ_Real)
      {Value in Base::First*Scale .. Base::Last*Scale} -> Float_With_Units;

    operator "to_univ"(Value : Float_With_Units) -> Result : Univ_Real
      {Result in Base::First*Scale .. Base::Last*Scale};

    operator "+"(Left, Right : Float_With_Units) -> Result : Float_With_Units
      {[[Result]] == [[Left]] + [[Right]]};

    operator "=?"(Left, Right : Float_With_Units) -> Ordering;

    operator "*"(Left : Float_With_Units; Right : Right_Type is Float_With_Units<>)
      -> Result : Result_Type is Float_With_Units<Unit_Dimensions =>
                                Unit_Dimensions + Right_Type.Unit_Dimensions>
        {[[Result]] == [[Left]] * [[Right]]};

    operator "/"(Left : Left_Type is ...
 end interface Float_With_Units;

 type Meters is Float_With_Units<Name => “centimeters”, Short_Hand => “cm”,
   Unit_Dimensions => [#m => 1.0, #k => 0.0, #s => 0.0], Scale => 0.01>;
```

Conclusions



- Static analysis hasn't reached the masses yet
- Integration into the development process is essential
  - Ideally into the compiler/linker
- Integration into the language is the ultimate step -- it becomes a non-optional part of the process
- When designing a new language, can unify and simplify
- Can focus on new issues
  - pervasive parallelism
  - integrated annotations enforced at compile-time
- Read the blog if you are interested...

http://parasail-programming-language.blogspot.com

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