Static Analysis of C Programs

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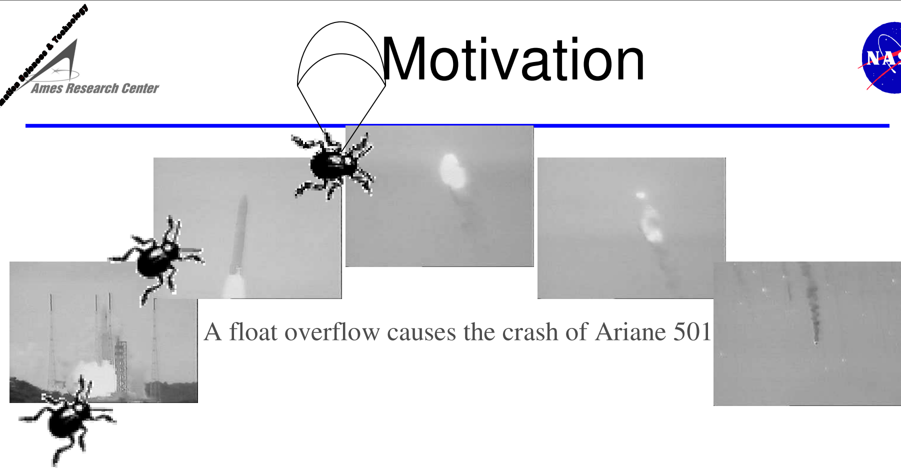
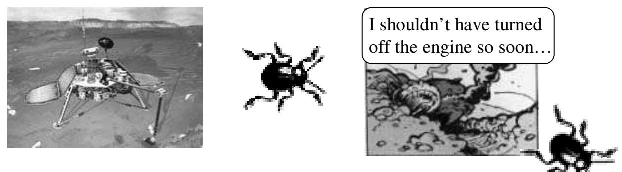
Agenda

- Motivation
- Introduction to Static Analysis
  - Definition
  - Defect classes
  - Applicability issues
  - Specialization
  - Analysis of MPF
- C Global Surveyor
  - Fact sheet
  - CGS phases
  - Example
- Conclusions

Motivation



A float overflow causes the crash of Ariane 501



A flag badly reset caused Mars Polar Lander to crash on Mars

Cost of Losing Missions

- Mars Polar Lander: > $150M
  - Development + Operations: $120M
  - Deep Space 2 probes: $30M
- Mars Climate Orbiter: ~$85M
  - Development: $85M
  - Operations: $5M
- Mars Surveyor 98 (MPL + MCO) $328M
  - Development: $193M
  - Launch: $92M
  - Operations: $43M
- Ariane 501: > $500M
  - Investment over 10 years: $7B
  - Payload value: $500M

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Static Analysis

- Static progam analysis consists of automatically discovering properties of a program that hold for all possible execution paths of the program
- Static analysis is **not**
  - Testing: manually checking a property for some execution paths
  - Model checking: automatically checking a property for all execution paths

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Static Analysis

all possible values (and more) are computed

the analysis is done without executing the program

Static analysis offers compile-time techniques for predicting Conservative, and computable, approximations to the set of values arising dynamically at run-time when executing the program

C Global Surveyor uses abstract interpretation techniques to extract a conservative system of semantic equations which can be resolved using lattice theory techniques to obtain numerical invariants for each program point

Is Static Analysis Useful?

- Optimizing compilers
- Program understanding
- Semantic preprocessing:
  - Model checking
  - Automated test generation
- **Program verification**
  - Discovering errors without executing the programs

Program Verification

- Check that every operation of a program will never cause an error (division by zero, buffer overrun, deadlock, etc.)
- Example:

```
int a[1000];
for (i = 0; i < 1000; i++) {
    a[i] = … ;   // 0 <= i <= 999
}
a[i] = … ;       // i = 1000;
```

safe operation → `a[i] = … ;   // 0 <= i <= 999`

buffer overrun → `a[i] = … ;   // i = 1000;`

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Defect Classes

- Static analysis is well-suited for catching runtime errors
  - Array-out-bound accesses
  - Un-initialized variables/pointers
  - Overflow/Underflow
  - Invalid arithmetic operations
- Also for program understanding
  - Data dependences
  - Control dependences
  - Slicing
  - Call graphs

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Defect Classes for DS1

- Defect classes for Deep Space One:
  - Concurrency: race conditions, deadlocks
  - Misuse: array out-of-bound, pointer mis-assignments
  - Initialization: no value, incorrect value
  - Assignment: wrong value, type mismatch
  - Computation: wrong equation
  - Undefined Ops: FP errors (tan(90)), arithmetic (division by zero)
  - Omission: case/switch clauses without defaults
  - Scoping Confusion: global/local, static/dynamic
  - Argument Mismatches: missing args, too many args, wrong types, uninitialized args
  - Finiteness: underflow, overflow

Issue 1: Incompleteness

- Discovering a sufficient set of properties (e.g., numerical invariants) for checking every operation of a program is an undecidable problem!
- **False positives:** operations that are safe in reality but which cannot be decided safe or unsafe from the properties inferred by static analysis.

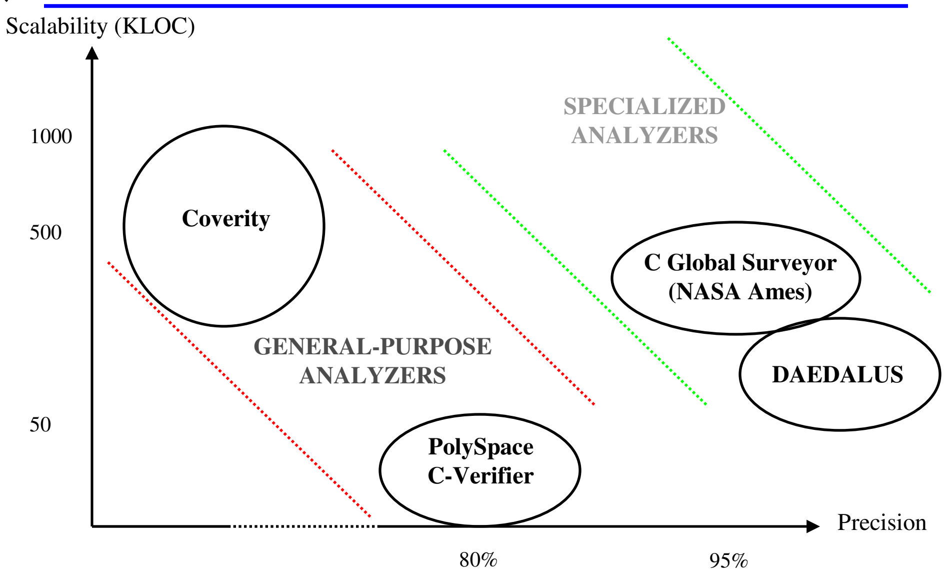
Issue 2: Precision

- **Precision:** number of program operations that can be decided safe or unsafe by an analyzer
  - Precision and computational complexity are strongly related
  - Tradeoff precision/efficiency: limit in the average precision and scalability of a given analyzer
  - Greater precision and scalability is achieved through **specialization**

Specialization

- Tailoring the analyzer algorithms for a specific class of programs
  - flight control systems
  - digital signal processing, …
- CGS is specialized for the MPF s/w family
- Precision and scalability is guaranteed for this class of programs only
  - However, CGS works for every C program
  - But precisision (and scalability) might not be as good for every C program as for MPF-based s/w

Practical Static Analysis



Analysis of MPF

- Analyzed 3 modules (~20KLoc each) of C code from the MPF flight software with PolySpace
- 80 % Precision
  - 80% checks have been classified (correct or incorrect) with certainty
  - 20% warnings: need to be covered by conventional testing
- Found 2 certain errors in 30 minutes
  - But, average run is 12 hours
  - Average time spent manually analyzing RTE is 0.5 hours
- CGS analyzes all 140 KLoc of MPF in 1.5 hours with an 80% precision
  - Some array bounds are not know by CGS because they are passed dynamically in messages

Analysis of DS1

Polyspace:
analyzing 20-40 KLoc modules
took 8-12 hours
with an 80% precision

C Global Surveyor:
analyzing all 280 KLoc of DS1
took 2-3 hours
with a 90% precision

CGS fact sheet

- Static analyzer for finding runtime errors in C programs
  - Out-of-bound array accesses
  - *Non-initialized variables*
  - *De-referencing null pointers*
  - Tested on MPF and DS1 flight software systems
- Developed (20 KLoc of C) at NASA Ames in ASE group
  - A. Venet: arnaud@email.arc.nasa.gov
  - G. Brat: brat@email.arc.nasa.gov
- Runs on Linux and Solaris platforms
  - RedHat Linux 2.4
  - SUN Solaris 2.8
- Analysis can be distributed over several CPUs
  - Using PVM distribution system
- Results available using SQL queries
  - To the PostgreSQL database
  - *Browser-based graphical interface*

Example

dbm_ex.c

```
Main () {
    int i,j;
    volatile k;

    for (i=0; i<8; i++) {
      for (j=0; j<I; j++) {
        k++;
      }
    }
    return;
}
```

Setting up Analysis

- Creating a database
  - `initdb cgsDB`
- Starting the database in a separate shell
  - `postmaster -i -D cgsDB`
- Starting the PVM distribution system
  - `pvm conf`
  - Where `conf` lists all available machines
- Go to source directory: say `src/`
- Creating the intermediate form
  - `cgsfe dbm_ex.c`
  - The file `dbm_ex.cil` is created in `src/CGS/`

Initialization

- First, CGS reads the CIL files and prepare for the analysis
  - `cgs init CGS/dbm_ex.cil`
- In the database, one can see file and function tables:
  - `psql src`
  - `select * from file_table;`
  - `select * from function_table;`

Building Equations

- The second of step of CGS consists of building the semantic equations abstracting the behavior of the program:
  - `cgs build <options>`
- This creates a table of equations in the database
  - Local numerical invariants available in DB
  - `select * from num_inv_table where function=<name>;`

Bootstraping

- This phase builds an abstract graph of the memory usage in the C program
  - `cgs bootstrap <option>`
- In the database the following information is now available:
  - Call graph
  - Memory graph, e.g., which global pointers points to what memory cell

Solving the Equations

- The next step is to solve the equations using the pointer analysis done in the previous phase
  - `cgs solve <options>`
- The following information is now available in the database:
  - Pointer table
  - All numerical invariants for all program points

ABC Analysis

- The only currently available analysis is the one checking the out-of-bound array accesses
  - `cgs abc`
- Results are available in the database
  - `select * from abc_result_table;`
  - Results are coded:
    - G for green: the access is correct
    - R for red: the access is incorrect
    - O for orange: the access may be incorrect
    - U for unreachable: dead code

Analysis Script for MPF

- cgs init CGS/*.cil (62s with eight 2.2MHz CPUs)
- cgs build –I –e –m Heap_alloc:2 –m IpcQ_Create:? –m BuggerMgr_alloc:? –s int-in-mem (527s)
- cgs bootstrap –c –k 3 –s taskSpawn:5 (445s)
- cgs solve –c –f –n (892s)
- cgs solve –c –b (471s)
- cgs solve –c –f –n (857s)
- cgs abc (510s) => roughly 1 hour for 60% precision
- cgs solve –c –b (526s)
- cgs solve –c –f –n (848s)
- cgs abc (503s) => roughly ½ hour for 80% precision

Conclusions

- Static analysis tools can be used to verify the absence of runtime errors in NASA code
  - No need for input test cases
  - Complete coverage of all data accesses (pointer aliasing) and execution paths
- Static analysis works well for errors such as
  - Out-of-bound array accesses
  - Un-initialized variables
  - De-references of null pointers
  - Some invalid arithmetic operations
- We have built a scalable, yet precise, static analyzer for C programs
  - Tested on MPF (140KLoc) and DS1 (280 KLoc)
  - Next test: MER (650 KLoc) and other NASA mission code
  - Available on Linux and Solaris platforms
- We plan on developing a static analyzer for MDS code
  - Will work for a simplified version of C++
  - Tentative availability date: 2005