Vertically Integrated Analysis and Transformation for Embedded Software

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Embedded Systems

- Most new microprocessors are embedded
  - Consumer electronics
  - Vehicle control systems
  - Medical equipment
  - Smart dust
Problem

- Compared to general-purpose compilation:
  - We have a lot more information
  - We have a lot more constraints
- So, using standard toolchain:
  - Ignores most of the information
  - Ignores most of the constraints
- However:
  - Strong economic incentive to avoid reinventing the wheel
Vertically Integrated Program Analysis (VIPA)

- Framework for combining analyses and transformations operating on a system at multiple levels of abstraction
(1) What good is gcc?

- Traditional C/C++ compilers pretty close to end of the line with respect to optimizing embedded SW
- However, C/C++ still useful for a while
- VIPA:
  - Keep the compiler around as a code generator
  - But do analysis and coarse-grain transformation in separate tools
(2) Tradeoffs are hard

- Embedded compilers must make difficult tradeoffs between goals
  - Power use, code size, data size, avoid crashing, etc...
  - Each embedded system has a different prioritization for these goals
- Standard compilers are ill-equipped to do what we want
  - Mechanism and policy all mixed up
(3) Levels of abstraction

- Analyses and transformations need to be performed at multiple levels of abstraction
  - Model – task mapping, exclusive modes, real-time deadlines
  - Source – concurrency, exceptions
  - Binary – memory usage, execution time, bit widths

- Standard compilers are ill-equipped to do what we want
(4) Tools are myopic

- Analysis tools often return binary results
  - “System is not schedulable”
  - “Network acceptor thread contains a potential stack overflow”
- Often more information is available but hidden
  - Which task is blocking schedulability?
  - What is the path to max stack depth?
- This information can be exploited
(5) Analysis good!

- Increasing asymmetry between
  - Resources on a PC and
  - Resources on a typical embedded system
- Program analysis and transformation tools are rapidly becoming more useful and effective
- The asymmetry can and should be exploited
VIPA Example 1

- **Given:**
  - Tool to compute a static upper bound on stack memory usage
  - Global function inlining tool

- **Goal:**
  - Reduce the stack memory requirements of an embedded system
Reducing Stack Depth
[EMSOFT 2003]

- Observation: Function inlining often decreases stack requirements
  - Avoids pushing registers, frame pointer, return address
  - Called code can be specialized

- Strategy: Use stack tool output as input to global inlining tool
Feedback Loop

C compiler (source) → stack analyzer (binary) → whole program inliner (source)

policy here → search heuristic
Challenges

1. **Inlining causes code bloat**
   - Solution: Minimize user-defined cost function that balances stack memory and code size

2. **Inlining sometimes increases stack depth!**
   - Solution: Trial compilations

3. **Search space is exponential in number of static function calls**
   - Solution: Heuristic search
Results

- Averaged over a bunch of TinyOS kernels…
  - 60% reduction in stack requirements compared to no inlining
  - 32% reduction compared to whole-program inlining not aimed at reducing stack depth
Result Details

- Maximum inlining
- Different tradeoffs in jointly minimizing stack size and code size
- No inlining
- nesC

Graph showing the relationship between code size (bytes) and upper bound on stack size (bytes).
VIPA Example 2

- **Given:**
  - WCET analysis
  - Synchronization analysis
    - Race / deadlock detection
  - Synchronization transformation
    - Lock elimination
    - Lock coarsening
  - Real-time-aware task mapping

- **Goal:** balance response time, efficiency, and memory use
Feedback Loop 2

- WCET analysis (binary)
- C compiler (source)
- Task mapping (model)
- Sync. transform. (source)
- Sync. analysis (source)
- Search heuristic
Given:
- Many, many tools that exist for analyzing and transforming embedded software

Goal:
- Rapidly produce efficient and reliable software
What is VIPA?

- Exchange formats for analysis results
  - Annotated callgraph
  - Annotated task set
  - Others?
    - Type and alias information
    - Heap allocation / deallocation protocols
- Tools “opened up” to read/write the exchange formats
What is VIPA? Cont’d

◆ Strategies for connecting tools
  ➢ E.g. feedback loops
◆ Policies
  ➢ Manage tradeoffs between goals
◆ Auxiliary tools (that don’t exist yet)
  ➢ GUI to help developers specify tradeoffs
  ➢ Manage interactions between analyses
Research Challenges

- Maintaining invariants
  - Transformations will invalidate some analysis results
- Avoiding bloat in the trusted computing base
  - Embedded developers have a hard time trusting even the compiler
- Avoiding long build times
- Providing good error messages
Related Work

- Phasing of optimizations inside compilers
- Model based design of embedded software
- MOBIES analysis interchange format
Conclusion

◆ Benefits for developers:
  ➢ Keep using the standard toolchain
  ➢ Write straightforward code
    ➢ Fewer fragile manual specializations
  ➢ Explicit support for meeting design goals in the presence of tradeoffs
    ➢ Policies externalized

◆ Benefit for researchers:
  ➢ Lots of cool tools out there – let’s make them play together
More info here:
http://www.cs.utah.edu/~regehr/