Embedded System Programming

WCET Analysis (1)
(Module 38)

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Execution Time – WCET & BCET

(Figure from R. Wilhelm et al., ACM Trans. Embed. Comput. Sys, 2007.)
The WCET Problem

Given
- the code for a software task
- the platform (OS + hardware) that it will run on

Determine the WCET of the task.

Why is this problem important?
- The WCET is central in the design of real-time computing

Can the WCET always be found?
- In general, not a decidability problem, but a complexity problem

Compute bounds for the execution times of instructions and basic blocks and determine a longest path in the basic-block graph of the program.
Components of Execution Time Analysis

- **Program path (Control flow) analysis**
  - Want to find longest path through the program
  - Identify feasible paths through the program
  - Find loop bounds
  - Identify dependencies amongst different code fragments

- **Processor behavior analysis**
  - For small code fragments (basic blocks), generate bounds on run-times on the platform
  - Model details of architecture, including cache behavior, pipeline stalls, branch prediction, etc.

- Outputs of both analyses feed into each other
Program Path Analysis: Overall Approach (1)

- Construct Control-Flow Graph (CFG) for the task
  - Nodes represent Basic Blocks of the task
    - Basic block: a sequence of consecutive program statements where there is no possibility of branching
    - We have a single entry and a single exit node
  - Edges represent flow of control (jumps, branches, calls, …)

- The problem is to identify the longest path in the CFG
  - Note: CFG can have loops, so need to infer loop bounds and unroll them
  - This gives us a directed acyclic graph (DAG). How do we find the longest path in this DAG?
Program Path Analysis: Overall Approach (2)

- In a CFG
  - $B_i$ = basic block $i$
  - $x_i$ = number of times the block $B_i$ is executed
  - $d_j$ = number of times edge is executed
  - $c_i$ = worst case running time of block $B_i$

- Objective: find

\[ WCET = \max_{x_i} \sum_{i=1}^{N} c_i x_i \]

- How to get $x_i$?
  - Structural constraints
  - Functionality constraints
  - Loop bounds -- need to be known
CFG Example

Example due to Y.T. Li and S. Malik

\[
\begin{align*}
N &= 10; \\
q &= 0; \\
\text{while}(q < N) & \quad q++; \\
q &= r;
\end{align*}
\]

\[
\begin{align*}
B1: & \quad N = 10; \\
& \quad q = 0; \\
B2: & \quad \text{while}(q < N) \\
& \quad q++; \\
& \quad q = r;
\end{align*}
\]

\[
\begin{align*}
B3: & \quad q++; \\
\end{align*}
\]

Want to maximize \( \sum_i c_i x_i \) subject to constraints:

- \( x_1 = d_1 = d_2 \)
- \( d_1 = 1 \)
- \( x_2 = d_2 + d_4 = d_3 + d_5 \)
- \( x_3 = d_3 = d_4 = 10 \)
- \( x_4 = d_5 = d_6 \)
/ * k >=0 */

s = k;

while (k < 10){
  if (ok)
    j++;
  else {
    j = 0;
    ok = true;
  }
  k++;
}

r = j;
Supplementary Slides