Static energy consumption analysis for LLVM IR programs

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Motivation

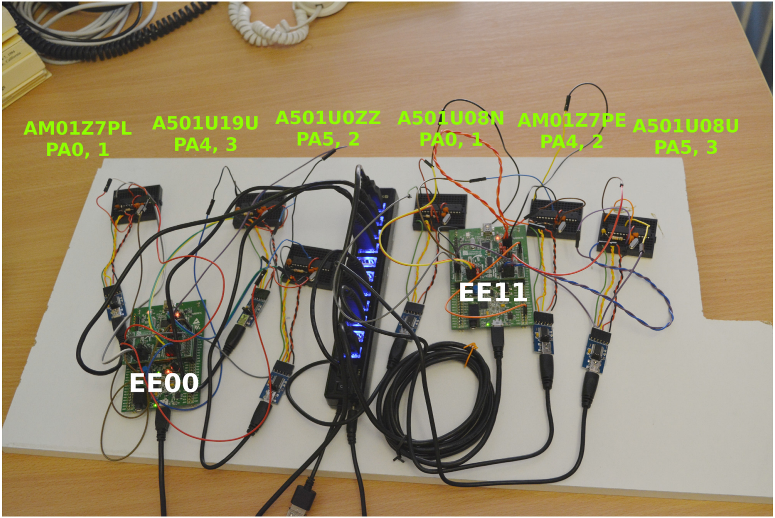
Software has final control of energy consumption:

- Instructions executed on processor causes circuit switching.
- Operation of software determines what clock domains can be gated.
- Amount of work performed by software determines how long the system draws power for.

Energy transparency enables decision making:

- Making energy information available to the developer allows for energy-based design decisions.
- Performing measurements requires dual-skill developers, instrumentation, and actual working hardware, presenting a burden to development.
- A solution then, is energy estimation from software.

Measuring energy is time consuming and complex.



Summary of our technique.

- Produce basic-block energy costs using processor energy model, and compiler infrastructure.
- Simplify program to make it ameanable to analysis.
- Extract cost relations (CRs), characterising the energy consumed by the program.
- Solve CRs and infer a closed form formula.

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Example, Levenshtein distance algorithm, i.e.:

- Initialize distance-table for string, length A.
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- For each element of A, for each element of B, calculate insert/delete/modify distance.

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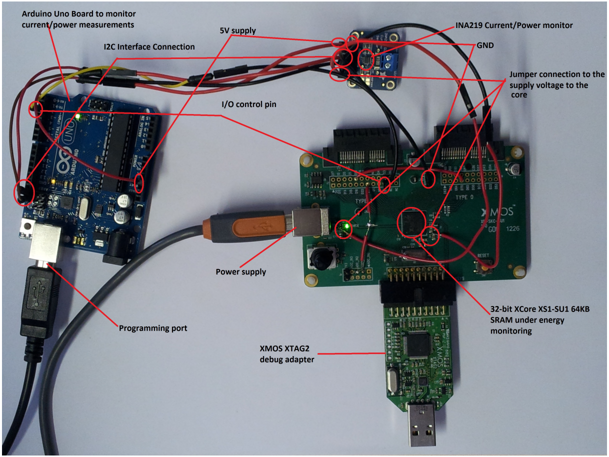
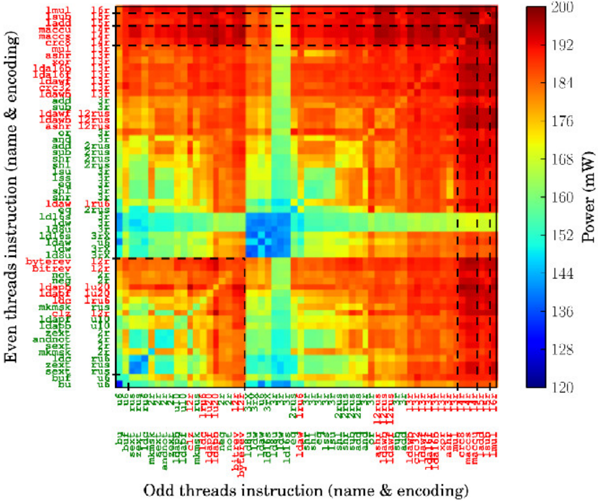
$$(A(53B + 16) + 35B + 31)\ \mathrm{nJ}, \tag{1}$$

Energy measuring, set up.



ISA Characterization



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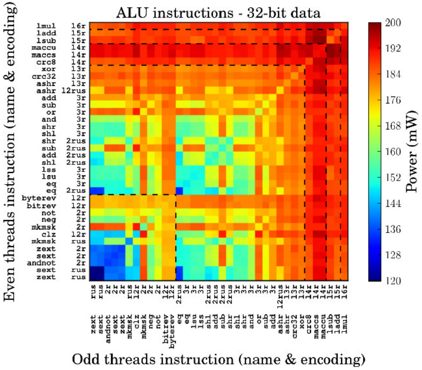
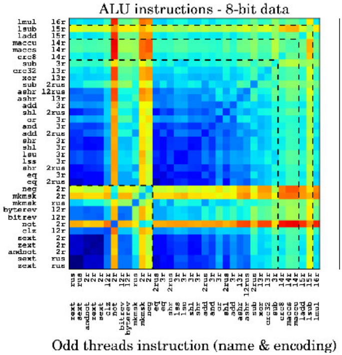




Understanding our processors

XMOS:

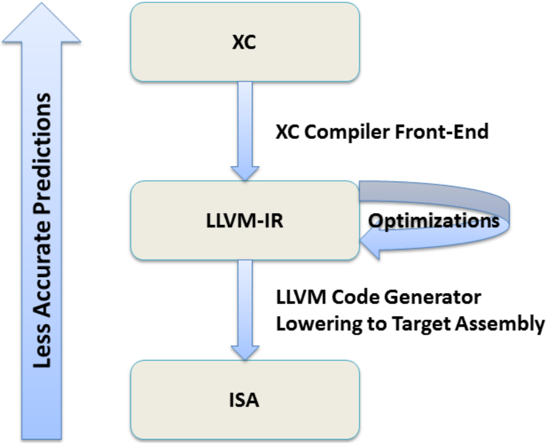
- Hardware multithreading microcontroller.
- No caches, branch prediction, or other timing unpredictable features.
- Designed for high frequency IO control.

ARM Cortex-M3:

- Instructions grouped by characteristics (memory access, control flow, division, other).
- Average energy collected for each group of instructions.
- Energy assigned to LLVM-IR instructions.

This energy model is less accurate than the XCore model, but required less effort to produce.

Mapping LLVM IR blocks to machine instructions



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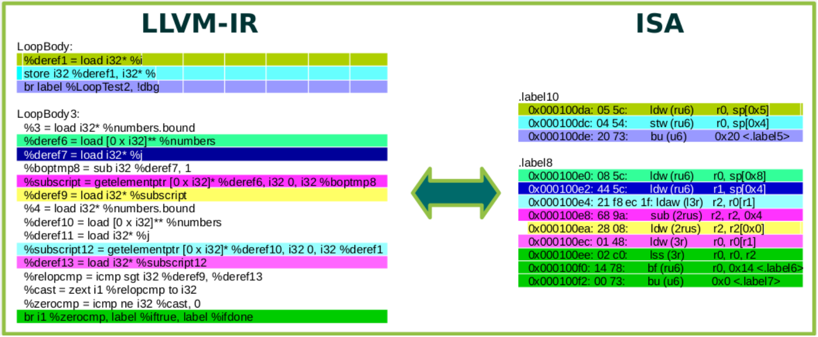

Resource Analysis Example

Original program

```
int fact(int i) {
 if (i<=0)^a
   return 1^b;
 return (i*^d fact(i-1))^c;
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$$C_{fact}(i) = C_a + C_b \qquad if\ i <= 0$$

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- Substitute C_a, C_b, C_d with actual energy required to execute low level instructions.
- Solve relations using off the shelf solvers to obtain *closed form* solution.
- Result: $C_{fact}(i) = 4563 + 7878i\ pJ$.

Linguistic Abstraction

Various language subsets of LLVM IR have been formalised. For analysis purposes, we abstract LLVM IR as follows:

$$
\begin{array}{rlr}
\mathit{inst} = & \text{br } p \ BB_1 \ BB_2 & \text{conditional branch instruction} \\
\mid & x = \text{op } a_1..a_n & \text{generic side effect-free operation} \\
\mid & x = \phi \ \langle BB_1, x_1 \rangle .. \langle BB_n, x_n \rangle & \text{phi nodes} \\
\mid & x = \text{call } f \ a_1 \ .. \ a_n & \\
\mid & x = \text{memload} & \text{dynamic memory load operation} \\
\mid & \text{memstore} & \text{dynamic memory store operation} \\
\mid & \text{ret } a &
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where metavariable names p,f,a,x are predicates, function names, generic arguments and variables respectively.

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Abstract semantics are standard, except:

- $x =$ memload simply invalidates x i.e., $x =?$.
- memstore may set any area in memory.

Building Cost Relations

Cost relations characterise the cost of executing a program or basic block, for example block a:

$$C_a(x, y) = S_a + C_b(x + n_1, y + m_1) + C_c(x + n_2, y + m_2) + \dots \text{ if condition}$$

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Next: How do we infer cost relations from existing programs?

Symbolic Evaluation

At the core of our resource analysis mechanism is a symbolic evaluation function *seval*.

- Given a block of code BB, and a variable x, $seval(BB, x)$ symbolically executes a slice from this block to produce a result.
- Abstracts away the effect of dynamic memory reads and writes, i.e., memload and memstore
- Hence we can produce simple expressions, which can be handled by existing solvers.

Symbolic Evaluation cont.

Symbolic evaluation is used:

- On branch predicates to infer side conditions for cost relations.
- To summarise the effect of executing a block on a variable (e.g. induction variable).

Example:

```
LoopIncrement:
  %postinc = add i32 %i.0, 1
  %exitcond = icmp eq i32 %postinc, %1
  br i1 %exitcond, label %return, label %LoopBody
```

In this case *seval*(BB,`%exitcond`) is (`%i.0`+1) =`%1`, found by traversing the structure of the LLVM block backwards.

Cost Relations Arguments

To simplify the analysis, we only consider variables and arguments that affect the control flow, e.g.:

```
int accumulate(int n) {
    int res = n;
    while (n--) res+=n;
    return res;
}
```

- Only the value of `n` affects the control flow, not `res`. CRs will therefore be parametric with `n`.
- Computed using data flow analysis techniques.

Analysing Nested Loop Structures

Certain classes of programs require further analysis/transformation.

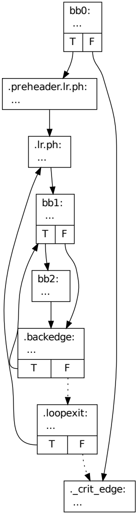
```
void bubbleSort(int numbers[], int array_size) {
  int i, j, temp;
  for (i = (array_size - 1); i >= 0; i--) {
    for (j = i; j > 0; j--)  {
      if (numbers[j-1] > numbers[j]) {
        temp = numbers[j-1];
        numbers[j-1] = numbers[j];
        numbers[j] = temp;
      }
    }
  }
}
```

Unfortunately, the high level loop structure is mangled by compiler optimisations.

LLVM IR (clang -O3)

```
define void @bubbleSort(i32* nocapture %numbers, i32 %array_size)  {
bb0:
  %i.02 = add nsw i32 %array_size, -1
  %1 = icmp sgt i32 %i.02, 0
  br i1 %1, label %.preheader.lr.ph, label %._crit_edge
.preheader.lr.ph:
  %2 = sext i32 %i.02 to i64
  br label %.lr.ph
.loopexit:
  %i.0 = add nsw i32 %i.03, -1
  %3 = icmp sgt i32 %i.0, 0
  %indvars.iv.next = add i64 %indvars.iv, -1
  br i1 %3, label %.lr.ph, label %._crit_edge
.lr.ph:
  %indvars.iv = phi i64 [ %2, %.preheader.lr.ph ], [ %indvars.iv.next, %.loopexit ]
  %i.03 = phi i32 [ %i.02, %.preheader.lr.ph ], [ %i.0, %.loopexit ]
  br label %bb1
bb1:
  %indvars.iv4 = phi i64 [ %indvars.iv, %.lr.ph ], [ %indvars.iv.next5, %.backedge ]
  %j.01 = phi i32 [ %i.03, %.lr.ph ], [ %5, %.backedge ]
  %5 = add nsw i32 %j.01, -1
  %6 = sext i32 %5 to i64
  %7 = getelementptr inbounds i32* %numbers, i64 %6
  %8 = load i32* %7, align 4,
  %9 = getelementptr inbounds i32* %numbers, i64 %indvars.iv4
  %10 = load i32* %9, align 4,
  %11 = icmp sgt i32 %8, %10
  br i1 %11, label %bb2, label %.backedge
.backedge:
  %12 = icmp sgt i32 %5, 0
  %indvars.iv.next5 = add i64 %indvars.iv4, -1
  br i1 %12, label %bb1, label %.loopexit
bb2:
  store i32 %10, i32* %7, align 4, !tbaa !0
  store i32 %8, i32* %9, align 4, !tbaa !0
  br label %.backedge
._crit_edge:
  ret void
}
```

Extracting Loop Structure



- The compiler turns nested loops into CFG structures without cover points (left).

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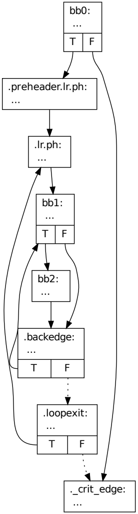
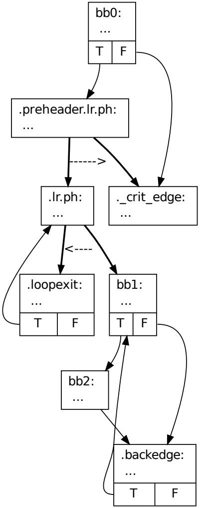


- The compiler turns nested loops into CFG structures without cover points (left).
- However, these can be transformed in a lot of cases (right).
- *Energy conservation semantics* preserved for typical `while` or `for` loops compiled by `clang` or `xcc`.



Benchmarks.

- Selection of benchmarks from existing suites .
  - Levenshtein distance, Matrix multiply (BEEBS).
  - Multiply-accumulate, JPEG DCT (WCET).
  - Additionally, insertion sort and base64 encoding algorithms.
- Each benchmark analyzed by our technique to produce a cost formula.
- Evaluated over a range of different input sizes to determine accuracy.

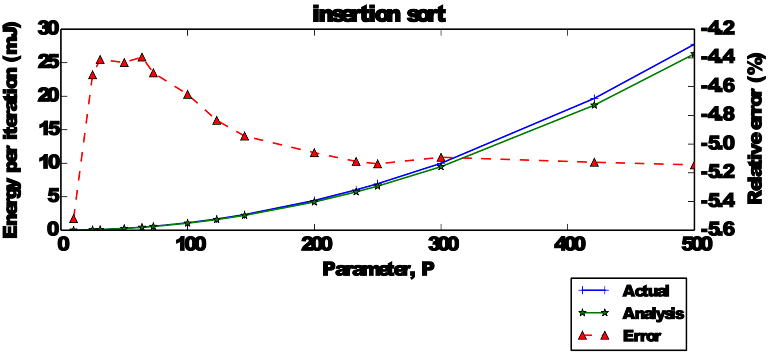
Formulae produced from benchmarks.

	ARM (nJ)	XMOS (nJ)
base64	$158 + 94 \cdot \left\lfloor \frac{P-1}{3} \right\rfloor$	$1270 + 734 \cdot \left\lfloor \frac{P-1}{3} \right\rfloor$
mac	$23P + 14$	$133P + 192$
levenshtein	$47AB + 14A + 31B + 44$	$559AB + 78A + 571 + \max(225B, 180B + 213)$
insertion sort	$25P^2 + 11P + 7.1$	$105P^2 + 30P + 75$
matrix multiply	$20P^3 + 13P^2 + 97P + 84$	$144P^3 + 200P^2 + 77P + 332$
jpegdct	54 mJ‡	463 mJ‡

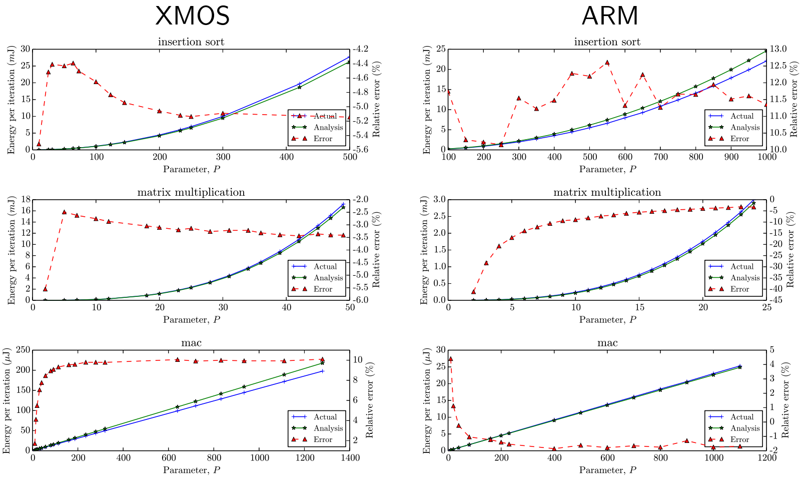
‡ This benchmark was not parametric, thus is not parameterised.

Table: Formulae and error values for each benchmark.

Example result.



Other results.



Discussion.

- Our energy estimations are within roughly 10% of measured energy for XMOS.
- Worse estimation for ARM, where we do not have a detailed energy model, but within 30% (most 15%).
- Generic technique (LLVM), requires either a detailed energy model, or as we have shown an approximation is sufficient too.
- The analysis itself requires little computational resources.
- Can be integrated into a development workflow.