EnergyAnalyzer:

Using Static WCET Analysis Techniques to Estimate the Energy Consumption of Embedded Applications

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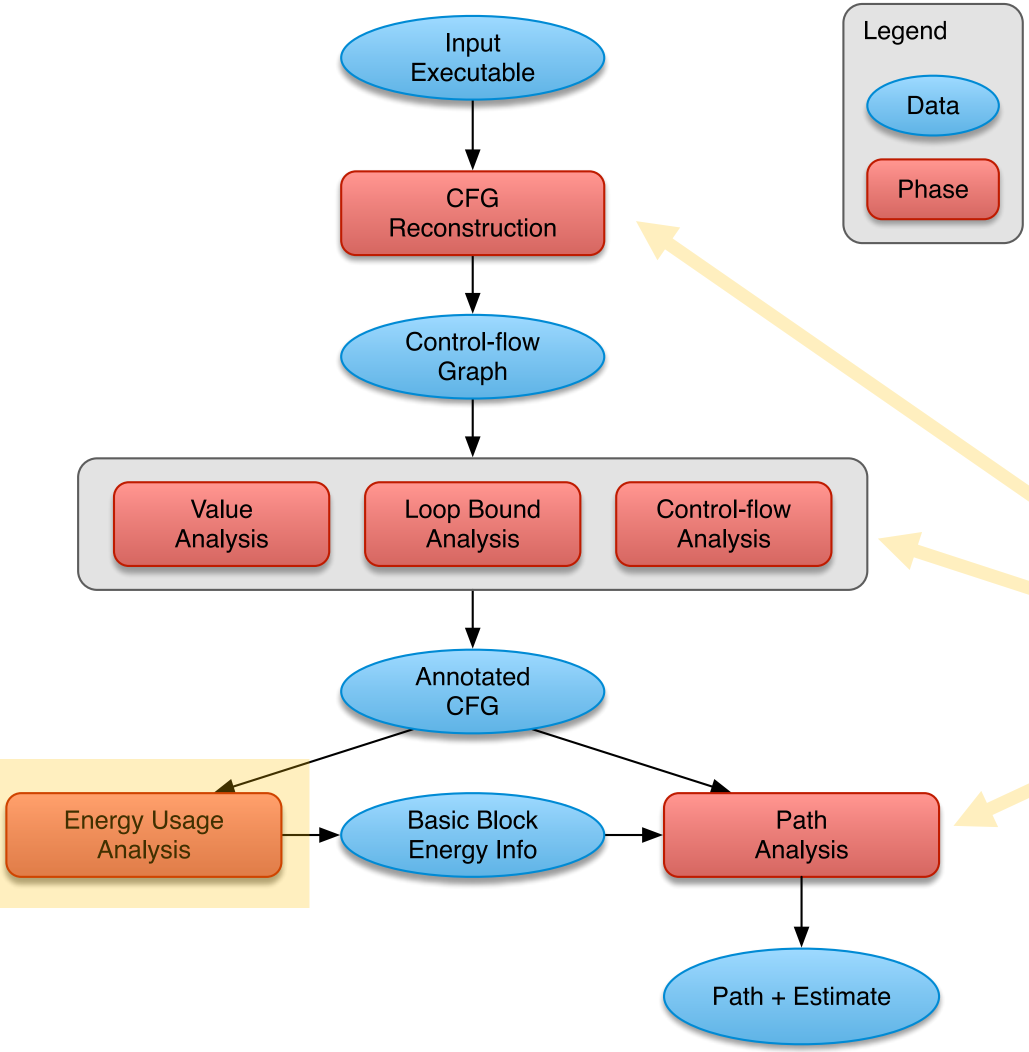
  - **Heiko Falk** and **Shashank Jadhav** for the integration of EnergyAnalyzer into WCC
  - Previous versions of the energy models have been generated by **Kyriakos Georgiou** and **Zbigniew Chamski**

Motivation

- Safety-critical systems must satisfy non-functional requirements
  - Computation must finish before a task reaches its deadline
  - Enough stack memory must be available for the system
- Solution: WCET/WCRT analysis, stack usage analysis
- What about energy-constrained systems?
- Idea: Apply techniques known from WCET analysis to statically estimate energy usage of embedded software

Tool Structure of EnergyAnalyzer



same as in aiT

Using energy models based on PMU counters

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Performance Monitoring Units

- PMUs are hardware units that track various events during the execution of software
- Examples:
  - Cache hits
  - Cache misses
  - Memory accesses
  - Number of executed instructions
  - …
- We use the PMU counters as proxy for energy usage

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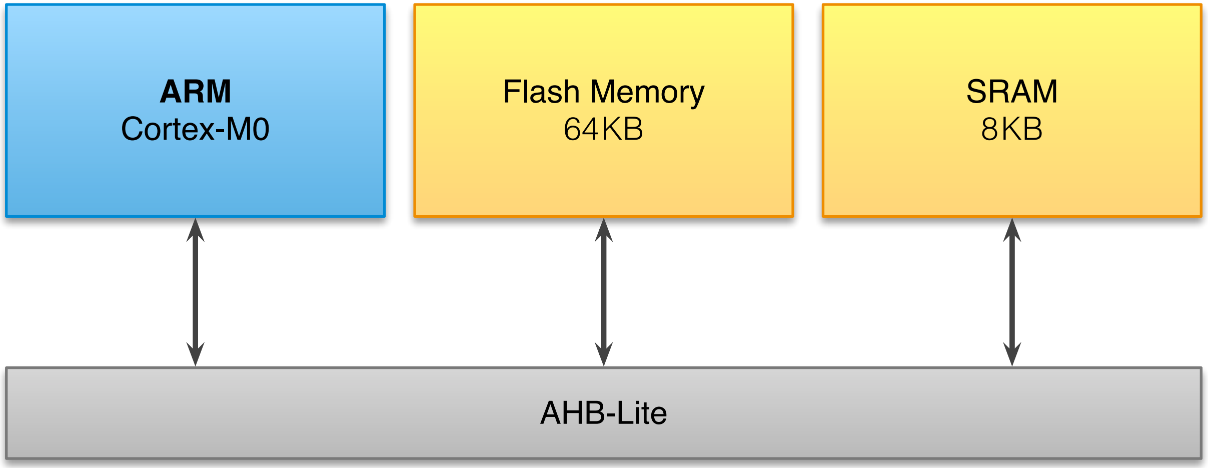
Energy Model Derivation

- Energy models are build using linear regression
  - We employed a Non-Negative Least Squares (NNLS) solver

- $E = \Sigma_x(\beta_x \times C_x) + \alpha$
  - where x are the various events tracked by PMU counters
  - C_x are the counter values
  - β_x are the coefficients of the model
  - α is the residual error term

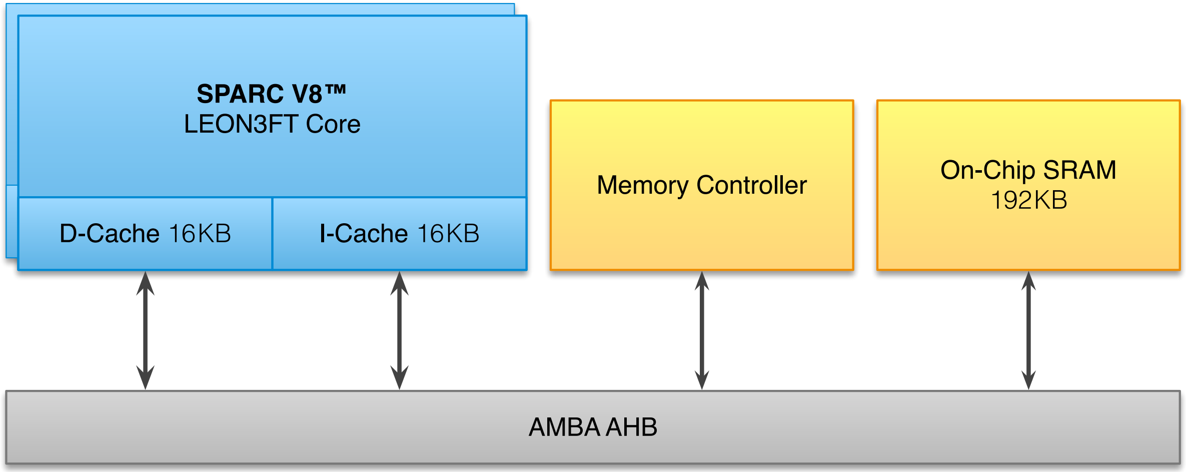
Target Architectures – ARM Cortex-M0

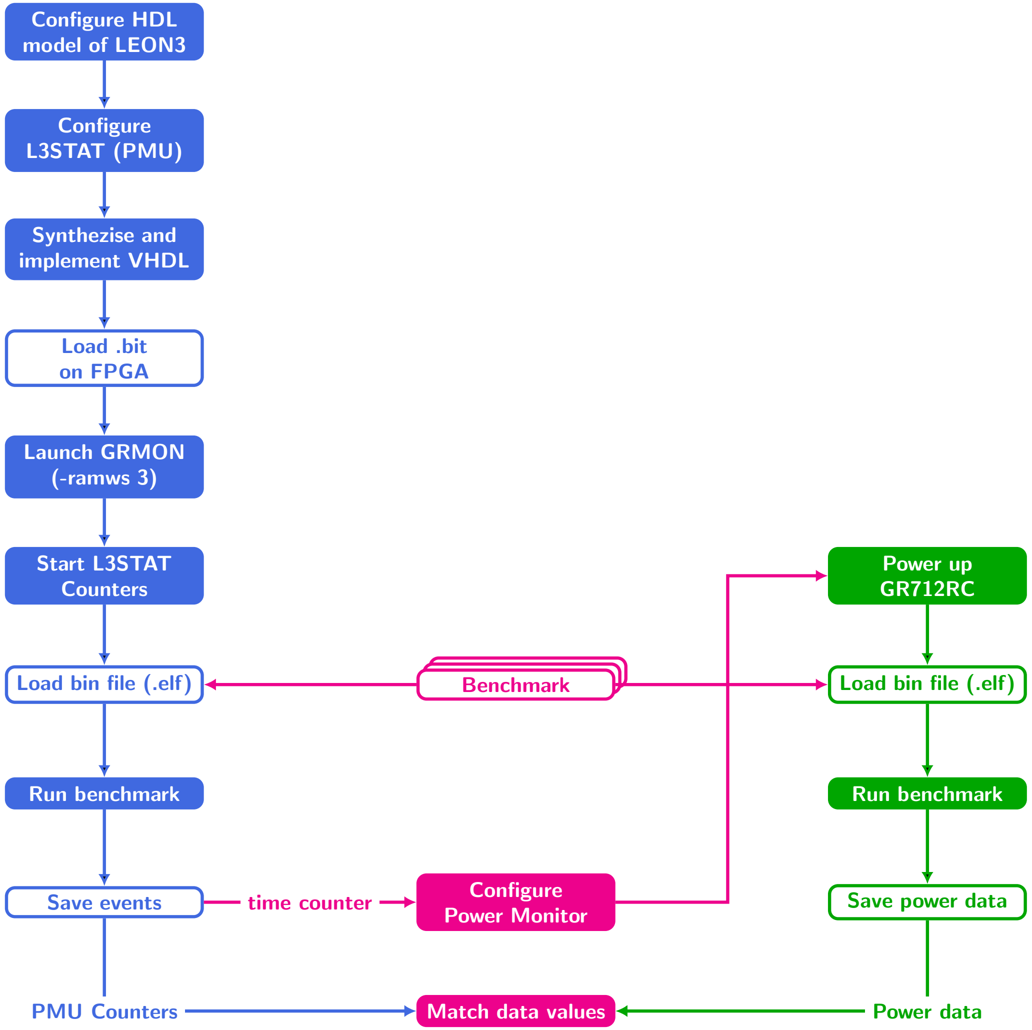
- Our specific target was the STM32F051R8T6
- This processor does not have a PMU
- We used `thumbulator`, an instruction set simulator, to count PMU events:
  - Executed instructions
  - Executed multiplication instructions
  - RAM reads
  - RAM writes
  - Flash reads
  - Taken branches



Target Architectures – LEON3

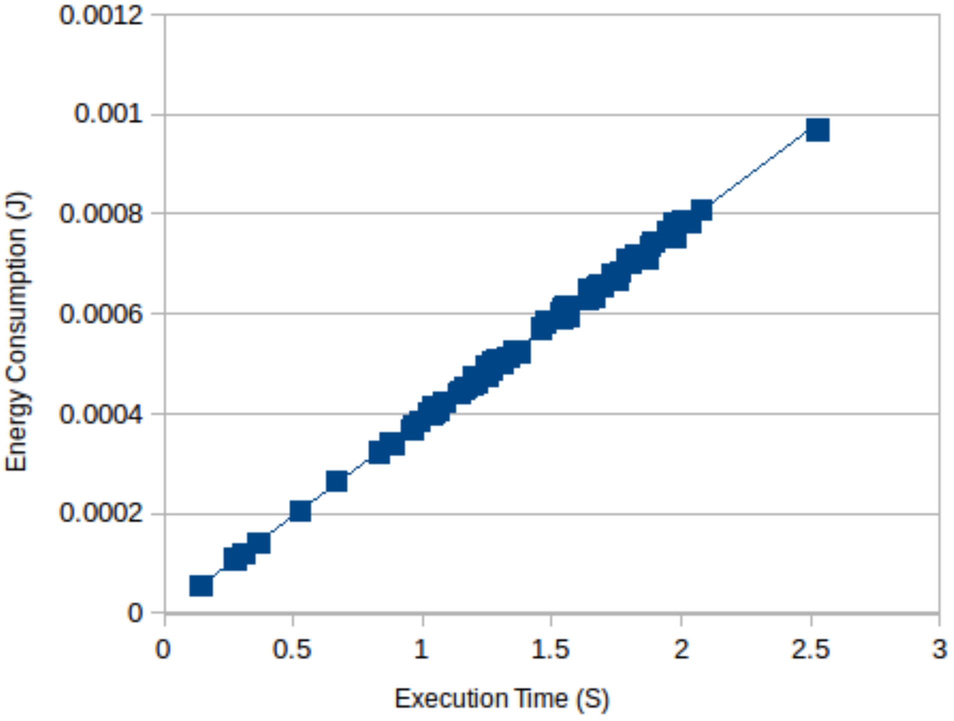
- Cobham Gaisler GR712RC
- A PMU (L3STAT) is available, but not included in this target
- We used a FPGA implementation of the LEON3 including L3STAT in sync with the original target





Energy Models – ARM Cortex-M0

- First energy model: time as proxy for energy [1, 2]
  - Derived using BEEBS benchmarks [3]
- E = 0.0004 W × t



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Energy Models – ARM Cortex-M0

- Second energy model: time as proxy for energy [4]
  - Derived using BEEBS benchmarks and Irida Labs‘ CNN benchmarks
  - The CNN benchmarks exercise much **more memory accesses**
- $E = 0.04387\ \mathrm{J} + 0.007242\ \mathrm{W} \times t$

Energy Models – ARM Cortex-M0

- Third energy model: PMU events as proxy for energy [5]
  - Derived using BEEBS benchmarks and Irida Labs‘ CNN benchmarks

$$
\begin{aligned}
E_{\text{Cortex-M0}} = {} & 0.972565030 \times C_{\text{executed instructions without multiplications}} \\
& + 0.652871770 \times C_{\text{RAM data reads}} \\
& + 1.031341343 \times C_{\text{RAM writes}} \\
& + 1.037625441 \times C_{\text{Flash data reads}} \\
& + 1.354953706 \times C_{\text{taken branches}} \\
& + 2.274650563 \times C_{\text{multiplication instructions}}
\end{aligned}
$$

Evaluation – ARM Cortex-M0

Benchmark	Analysis Result	Model Result	Δ	Note
aha-compress	78.885 mJ	78.828 mJ	< 1 %	
aha-mont64	99.396 mJ	99.396 mJ	< 1 %	
bubblesort	366.763 mJ	366.762 mJ	< 1 %	
cnt	42.813 mJ	42.804 mJ	< 1 %	
compress	27.895 mJ	27.895 mJ	< 1 %	
crc	9.623 mJ	9.623 mJ	< 1 %	
cubic	7.801 J	4.138 J	89 %	flow constraints
duff	4.349 mJ	4.349 mJ	< 1 %	
edn	302.762 mJ	302.762 mJ	< 1 %	
expint	43.315 mJ	43.315 mJ	< 1 %	
fac	2.934 mJ	2.904 mJ	1 %	
fasta	29.383 J	21.100 J	39 %	flow constraints
fdct	12.292 mJ	12.292 mJ	< 1 %	
fibcall	1.493 mJ	1.493 mJ	< 1 %	
fir	1.994 J	1.994 J	< 1 %	
frac	1.183 J	1.183 J	< 1 %	
insertsort	3.089 mJ	3.089 mJ	< 1 %	
janne_complex	1.402 mJ	1.402 mJ	< 1 %	
jfdctint	31.481 mJ	31.476 mJ	< 1 %	
lcdnum	886.941 uJ	805.000 mJ	10 %	
levenshtein	400.926 mJ	400.926 mJ	< 1 %	
ludcmp	174.559 mJ	174.559 mJ	< 1 %	
matmult-float	1.537 J	1.537 J	< 1 %	
matmult-int	842.724 mJ	842.649 mJ	< 1 %	
minver	131.316 mJ	84.348 mJ	56 %	flow constraints
nbody	25.844 J	25.844 J	< 1 %	
ndes	293.387 mJ	293.297 mJ	< 1 %	

Benchmark	Analysis Result	Model Result	Δ	Note
nettle-arcfour	105.880 mJ	105.880 mJ	< 1 %	
nettle-cast128	23.214 mJ	23.211 mJ	< 1 %	
nettle-des	22.595 mJ	22.595 mJ	< 1 %	
nettle-md5	5.467 mJ	5.467 mJ	< 1 %	
nettle-sha256	50.507 mJ	50.507 mJ	< 1 %	
newlib-exp	70.439 mJ	70.439 mJ	< 1 %	
newlib-log	52.954 mJ	52.954 mJ	< 1 %	
newlib-sqrt	10.289 mJ	10.289 mJ	< 1 %	
nsichneu	61.017 mJ	29.185 mJ	109 %	
picojpeg	4.885 J	4.885 J	< 1 %	
prime	209.663 mJ	209.663 mJ	< 1 %	
qsort	27.294 mJ	20.408 mJ	34 %	flow constraints
qurt	139.891 mJ	139.890 mJ	< 1 %	
rijndael	7.176 J	7.042 J	2 %	
sglib-arraybinsearch	76.596 mJ	76.596 mJ	< 1 %	
sglib-arrayheapsort	86.857 mJ	86.857 mJ	< 1 %	
sglib-arrayquicksort	65.600 mJ	65.600 mJ	< 1 %	
sglib-queue	126.250 mJ	126.250 mJ	< 1 %	
slre	206.734 mJ	206.734 mJ	< 1 %	
sqrt	11.529 J	11.529 J	< 1 %	
st	4.142 J	2.945 J	41 %	flow constraints
statemate	13.331 mJ	9.308 mJ	43 %	
stb_perlin	5.145 J	5.145 J	< 1 %	
stringsearch1	46.362 mJ	46.362 mJ	< 1 %	
strstr	5.480 mJ	5.480 mJ	< 1 %	
trio-snprintf	105.378 mJ	65.427 mJ	61 %	flow constraints
trio-sscanf	139.345 mJ	71.618 mJ	95 %	flow constraints
ud	21.863 mJ	21.862 mJ	< 1 %	
whetstone	22.533 J	16.687 J	35 %	flow constraints

Table 1: Evaluation of the energy model integration into EnergyAnalyzer for ARM Cortex-M0

Energy Models – ARM Cortex-M0

- Even more energy models: PMU events as proxy for energy
  - The ARM Cortex-M0 allows a diversity of system configurations:
    - Frequency can bei either 20, 24, or 48 MHz
    - The instruction prefetch buffer can be enabled or not
    - Flash memory can be accessed with 0 or 1 waitstate
  - In total, the processor manual permits 10 combinations

Hardware Config.	Energy Consumption Model [nJ]	Meas. Energy[J]	MAPE [%]
[20, OFF, 0]	$E = 0.964258 \times C_1 + 1.652455 \times C_2 + 2.091986 \times C_3 + 1.109833 \times C_4 + 0.650563 \times C_5 + 0.633621 \times C_6$	221.4	2.80
[20, OFF, 1]	$E = 1.282474 \times C_1 + 2.110668 \times C_2 + 2.191545 \times C_3 + 1.185609 \times C_4 + 0.416602 \times C_5 + 1.178991 \times C_6$	274.9	2.97
[20, ON, 0]	$E = 1.003378 \times C_1 + 1.885309 \times C_2 + 1.802974 \times C_3 + 1.122833 \times C_4 + 0.849223 \times C_5 + 0.475831 \times C_6$	226.38	2.86
[20, ON, 1]	$E = 0.895879 \times C_1 + 2.185851 \times C_2 + 2.001178 \times C_3 + 1.493364 \times C_4 + 1.076354 \times C_5 + 1.573758 \times C_6$	227.9	3.68
[24, OFF, 0]	$E = 0.959172 \times C_1 + 1.888565 \times C_2 + 1.357556 \times C_3 + 1.089427 \times C_4 + 0.993145 \times C_5 + 0.562952 \times C_6$	214.62	3.22
[24, OFF, 1]	$E = 1.178558 \times C_1 + 2.540429 \times C_2 + 2.042475 \times C_3 + 1.190892 \times C_4 + 0.979651 \times C_5 + 0.891088 \times C_6$	264.88	3.16
[24, ON, 0]	$E = 0.985415 \times C_1 + 1.933276 \times C_2 + 1.448160 \times C_3 + 1.075671 \times C_4 + 1.011891 \times C_5 + 0.617510 \times C_6$	220.03	3.36
[24, ON, 1]	$E = 0.883755 \times C_1 + 2.156046 \times C_2 + 1.633465 \times C_3 + 1.436556 \times C_4 + 1.152560 \times C_5 + 1.455166 \times C_6$	220.05	4.15
[48, OFF, 1]	$E = 1.096677 \times C_1 + 2.364495 \times C_2 + 1.627854 \times C_3 + 1.173680 \times C_4 + 0.681475 \times C_5 + 0.652665 \times C_6$	243.44	3.65
[48, ON, 1]	$E = 0.816331 \times C_1 + 2.014612 \times C_2 + 1.372157 \times C_3 + 1.402116 \times C_4 + 0.835035 \times C_5 + 1.250446 \times C_6$	202.5	4.33

TABLE II: Energy models for selected Cortex-M0 hardware configurations – Hardware Configuration Format: [Frequency (MHz), PreFetch (ON/OFF), WaitState (0/1)] and MAPE: Mean Absolute Percentage Error

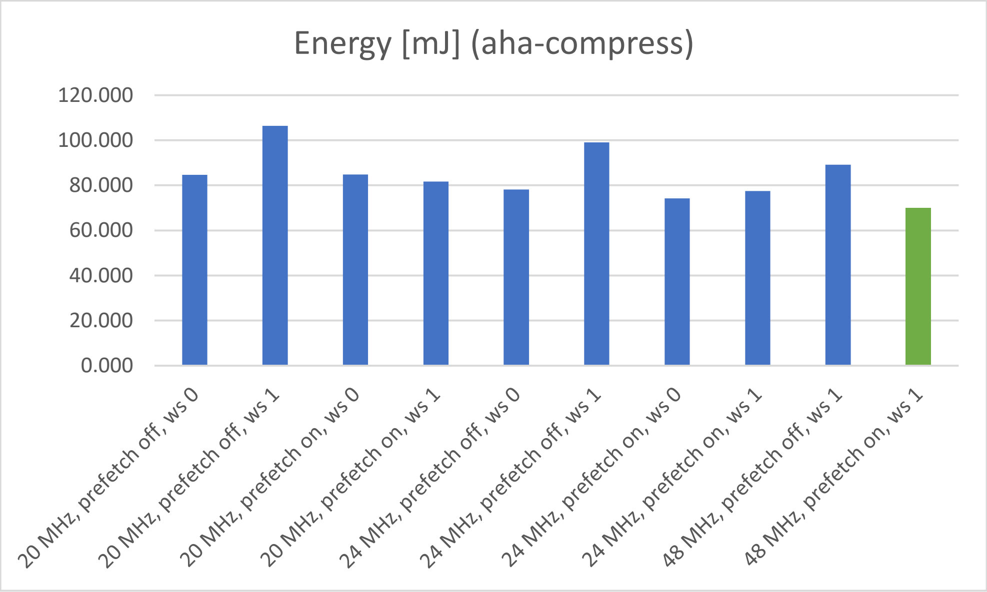
(taken from [6])

Energy Models – ARM Cortex-M0

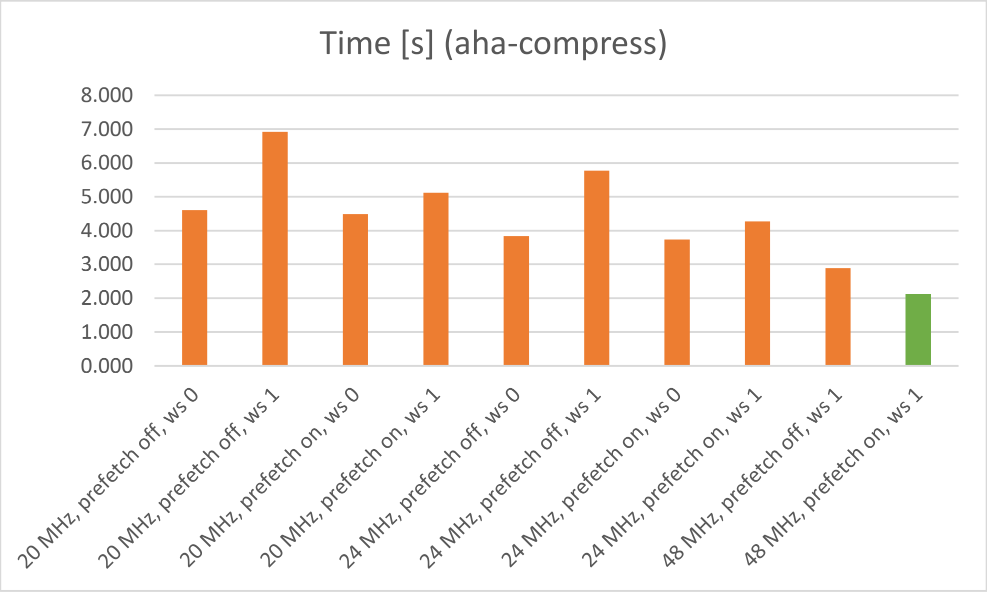
- EnergyAnalyzer allows to specify an energy model based on PMU counters

```
# EnergyAnalyzer specific attributes, all values have been rounded up to full pJ.
attribute "arm_event_energy_costs": {
    "instruction_fetch" = 973,
    "ram_data_write" = 1032,
    "ram_data_read" = 653,
    "flash_data_read" = 1038,
    "mul_instruction" = 1303,
    "taken_branch" = 1355
};
```

Energy Models – ARM Cortex-M0



(a) Comparison of different hardware configurations concerning energy usage



(b) Comparison of different hardware configurations concerning execution time

LEON3

- LEON3 PMU (L3STAT) has many available counters, not all of them being statically predictable
- Energy model has been build using the *ISA+Cache* subset of PMU counters

$$E_{\text{LEON3}} = 3.93365 \times 10^{-08} \times C_{\text{integer instructions}} + 1.87111 \times 10^{-07} \times C_{\text{store instructions}}$$

#	**Counter**	Description	#	**Counter**	Description
C_1	ICMISS	instruction cache misses	C_{13}	TYPE2	type 2 instructions
C_3	DCMISS	data cache misses	C_{14}	LDST	load and store instructions
C_7	IINST	integer instructions	C_{15}	LOAD	load instructions
C_{11}	BRANCH	branch instructions	C_{16}	STORE	store instructions
C_{12}	CALL	call instructions			

Table 2: *ISA+Cache* subset of L3STAT counters

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LEON3

- Other subsets are viable, too
  - However, the static prediction of those are less precise

Model	Expression	MAPE[%]	
		Train	Test
Energy [J] All Supported All Events	$E = 0.155261 + 2.94155\text{e-}08 \times C_0 + 2.5661\text{e-}09 \times C_2 + 9.93453\text{e-}09 \times C_5 + 8.97535\text{e-}10 \times C_{12} + 3.21255\text{e-}09 \times C_{13} + 6.14384\text{e-}09 \times C_{15} + 4.54827\text{e-}08 \times C_{16}$	1.14	0.29
Energy [J] All Supported Bottom-Up	$E = 0 + 3.19557\text{e-}08 \times C_0 + 5.79224\text{e-}08 \times C_{16}$	1.20	1.38
Energy [J] All Supported Top-Down	$E = 0.131077 + 3.13122\text{e-}08 \times C_0 + 9.17778\text{e-}09 \times C_5 + 2.99043\text{e-}09 \times C_{15} + 3.92999\text{e-}08 \times C_{16}$	1.02	1.54
Energy [J] All Supported Full-Exhaustive	$E = 0.131087 + 3.13122\text{e-}08 \times C_0 + 9.17779\text{e-}09 \times C_5 + 2.99043\text{e-}09 \times C_{14} + 3.63095\text{e-}08 \times C_{16}$	1.02	1.54
Energy [J] IsaCache All Events	$E = 0 + 1.18567\text{e-}06 \times C_3 + 5.9072\text{e-}07 \times C_{12} + 3.88949\text{e-}08 \times C_{13} + 8.03337\text{e-}08 \times C_{14} + 6.89885\text{e-}08 \times C_{16}$	8.38	24.03
Energy [J] IsaCache Bottom-Up	$E = 0 + 3.93365\text{e-}08 \times C_7 + 1.87111\text{e-}07 \times C_{16}$	5.84	8.24
Energy [J] IsaCache Top-Down	$E = 0 + 3.93365\text{e-}08 \times C_7 + 1.87111\text{e-}07 \times C_{16}$	5.84	8.24
Energy [J] IsaCache Full-Exhaustive	$E = 0 + 3.93365\text{e-}08 \times C_7 + 1.87111\text{e-}07 \times C_{16}$	5.84	8.24

Table 3: Different energy models for LEON3 based on two different subsets of PMU counters and different search strategies

Evaluation – LEON3

Benchmark	Analysis Result	Model Result	Δ	Note
aha-compress	11.004 J	11.004 J	0 %	
aha-mont64	7.499 J	7.491 J	< 1 %	
bubblesort	3.898 J	3.889 J	< 1 %	
edn	39.186 J	39.186 J	0 %	
fir	159.469 J	159.469 J	0 %	
frac	59.391 J	59.339 J	< 1 %	
levenshtein	25.506 J	25.491 J	< 1 %	
ludcmp	10.992 J	10.814 J	2 %	
matmult-float	2.847 J	2.822 J	1 %	
minver	14.372 J	4.643 J	210 %	worst-case
minver	7.398 J	4.643 J	59 %	assumptions
nbody	4.512 J	4.496 J	< 1 %	
ndes	24.828 J	24.467 J	1 %	

Benchmark	Analysis Result	Model Result	Δ	Note
nettle-aes	19.401 J	19.389 J	< 1 %	
nettle-arcfour	9.644 J	9.639 J	< 1 %	
nettle-sha256	2.763 J	2.754 J	< 1 %	
newlib-exp	4.374 J	4.319 J	1 %	
newlib-log	3.284 J	3.252 J	1 %	
picojpeg	503.732 J	503.918 J	< -1 %	traps
prime	3.670 J	3.667 J	< 1 %	
qurt	8.001 J	7.958 J	1 %	
sglib-arraybinsearch	6.283 J	6.281 J	< 1 %	
sglib-arrayheapsort	13.066 J	13.062 J	< 1 %	
sglib-arrayquicksort	13.066 J	13.052 J	< 1 %	
sglib-queue	13.901 J	13.900 J	< 1 %	
slre	14.988 J	15.261 J	-2 %	traps

Table 4: Evaluation of the *ISA+Cache* energy model integration into EnergyAnalyzer for LEON3

Emulating Floating-point Operations in Software

- The IEEE 754 standard for floating-point arithmetic defines data formats for floating-point numbers
  - Single precision floating-point number consists of one sign bit, eight bits for the exponent, and 24 bits for the mantissa
  - Only 23 bits of the mantissa are explicitly stored
  - The first bit of the mantissa is implicitly stored and assumed to be 1 for normalised numbers, and 0 for subnormal numbers
  - Subnormal numbers are used to represent numbers near zero with tiny absolute value, which cannot be represented as normalised numbers

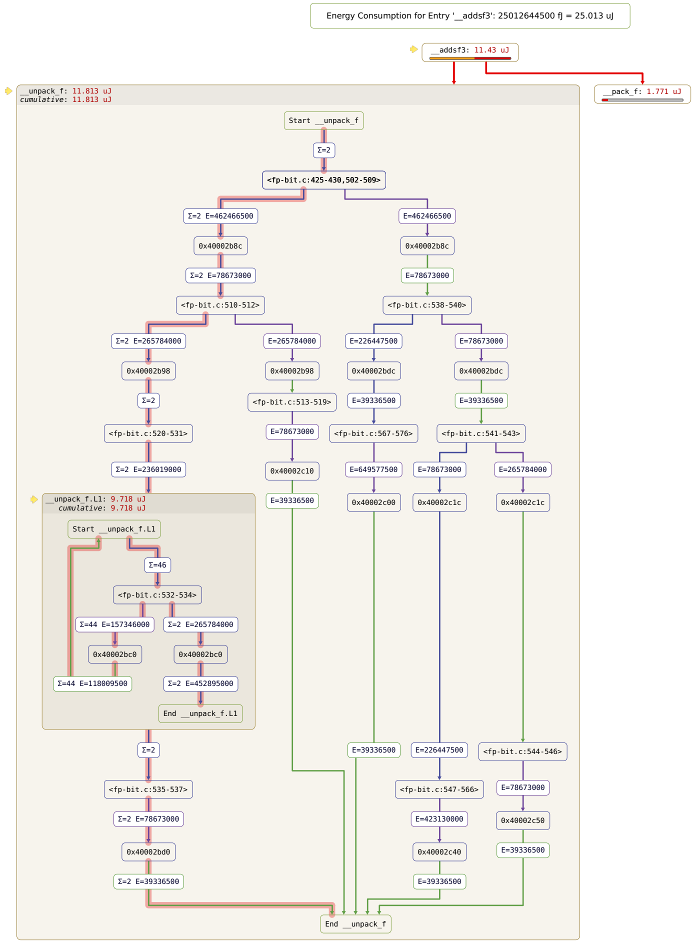
Emulating Floating-point Operations in Software

- Operations on subnormal numbers are usually more costly than operations on normalised numbers because they need to be scaled first before the actual operation is performed
  - Knowing whether a floating-point number is normalised or not has a huge impact on the analysis precision

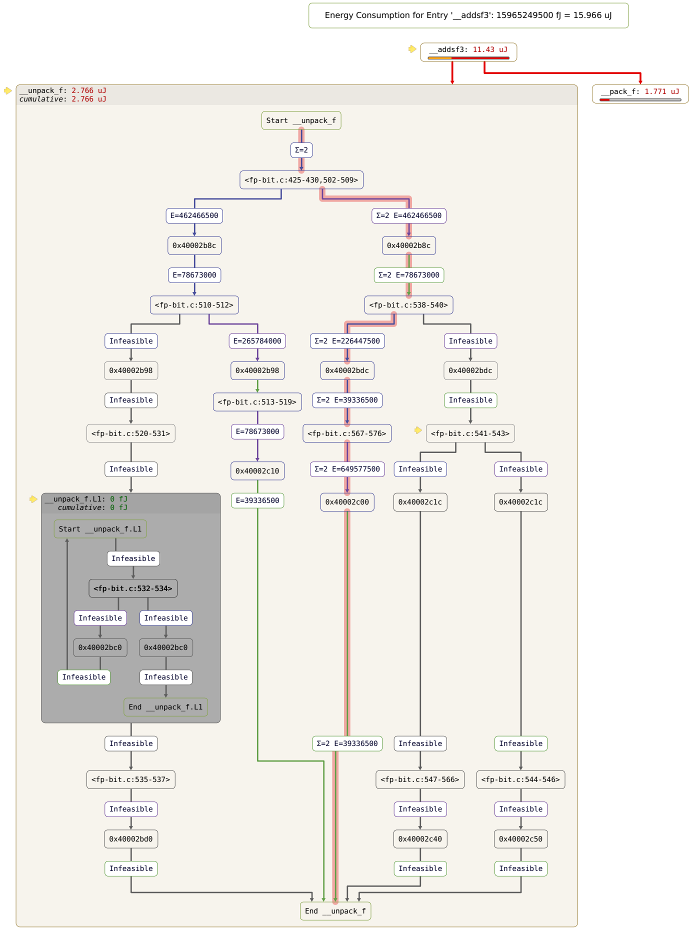
Routine	Worst-case Result	Result under Assumptions
`__mulsf3`	40.167 µJ	9.839 µJ
`__addsf3`	25.013 µJ	15.966 µJ
`__subsf3`	25.279 µJ	16.232 µJ
`__divsf3`	29.753 µJ	20.518 µJ
`__ieee754_sqrt`	180.879 µJ	113.977 µJ
`__muldf3`	85.228 µJ	14.225 µJ
`__adddf3`	76.141 µJ	42.784 µJ
`__subdf3`	76.367 µJ	43.010 µJ
`__divdf3`	103.489 µJ	69.945 µJ

Table 2.12: Analysis results using the *ISA+Cache* energy model for some routines of the software floating-point library. (taken from [7])

Emulating Floating-point Operations in Software



(a) Worst-case analysis of a software floating-point routine



(b) Assuming only normals and zero

Conclusion

- EnergyAnalyzer for ARM Cortex-M0 and LEON3 ...
  - are powerful tools for the development of embedded systems with energy constraints
  - allow to make informed decisions regarding hardware and compiler configurations
  - are versatile and allow to adapt the used energy model to the concrete platform
- Both tools have been integrated into the TeamPlay toolchain and successfully applied to various use cases [9]:
  - Multi-criterial optimization in WCC
  - Contract-based programming with CSL
  - Camera pill, CNN kernels, satellite software

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