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Energy-Aware Software Engineering

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Abstract

A great deal of energy in Information and Communication Technology (ICT) systems can be wasted by software, regardless of how energy-efficient the underlying hardware is. To avoid such waste, programmers need to understand the energy consumption of programs during the development process rather than waiting to measure energy after deployment. Such understanding is hindered by the large conceptual gap from hardware, where energy is consumed, to high-level languages and programming abstractions. The approaches described in this chapter involve two main topics: energy modelling and energy analysis. The purpose of modelling is to attribute energy values to programming constructs, whether at the level of machine instructions, intermediate code or source code. Energy analysis involves inferring the energy consumption of a program from the program semantics along with an energy model. Finally, the chapter discusses how energy analysis and modelling techniques can be incorporated in software engineering tools, including existing compilers, to assist the energy-aware programmer to optimise the energy consumption of code.

Keywords: energy modelling, energy analysis, energy transparency, energy aware, software engineering

1. Introduction

Energy-aware software engineering concerns the use of tools and methods to allow energy consumption to be a first-class software design goal. A design goal could be, for instance, to meet stated energy targets such as battery lifetime or power-supply constraints for a given ICT application running on a given hardware platform or simply to optimise energy efficiency.

Very few programmers at present have much idea of how much energy their programs consume or which parts of a program use the most energy. Therefore energy-related design goals are usually not considered until the programs are deployed; at that point, if energy goals are not reached, it may result in very long expensive redevelopment cycles.

Although energy is ultimately consumed by physical processes in the hardware, the software controls the hardware and indeed typically causes a great deal of energy waste by the inefficient use of the hardware. This waste cannot be recovered by relying on the development of more energy-efficient hardware—increasing the energy efficiency of the software is an essential part of reducing overall energy consumption [1]. Energy awareness for software development thus requires an understanding of the implications for energy consumption of design decisions in the software. In short, there is a need for *energy transparency*: the ability of the software developer to “see” the program’s energy consumption, ideally without actually executing and measuring it.

Chapter outline. Section 1 presents the background and motivation for energy-aware software engineering. Then the main scientific and technical foundations that support energy transparency are summarised. These are *energy modelling* and *static energy analysis*. Energy modelling (Section 2) concerns building models of software energy consumption at different levels of abstraction, attributing energy consumption at the hardware level to software constructs such as operations, instructions, statements, functions and procedures. Energy analysis (Section 3) concerns the estimation, using an energy model, of the energy that would be consumed when running a piece of software, without actually executing it. This estimate can be parameterised by the input data for the software or other contextual information.

Section 4 contains a summary of the typical sources of energy inefficiency that can be removed when the programmer has relevant information on energy consumption. Finally, Section 5 describes how software designers and developers can use energy transparency during the software engineering process and what kind of activities constitute “energy-aware software engineering.” For example, the programmer can analyse the program to identify which part of the software consumes most energy or explore the effect on energy consumption of different algorithms and data structures.

In contrast to much work on energy efficiency of ICT, this chapter adopts a generic approach, not driven by any particular class of applications, platforms or programming languages. The topic is currently mainly studied in different application contexts, such as embedded systems, high-performance systems, mobile systems and so on rather than as a coherent set of techniques applicable to any software-based system.

2. Energy-aware software engineering and Green IT

Concern over the increasing energy consumption and general environmental impact of ICT systems is growing. As a part of this, there has been a growth of interest in the field of *Green IT* [2–5] since approximately 2010; for example, the conference series International Green

And Sustainable Computing Conference¹ started in 2011 and the IEEE technical area of green computing² was launched in 2010. The Energy Aware COmputing workshop series³ was initiated in Bristol in 2011. More recently, dedicated workshops such as GREENS⁴ and SMARTGREENS⁵ have been launched.

Green IT covers energy aspects of the complete life cycle and context of ICT systems, including software and hardware, development energy costs, maintenance and deployment energy costs, cooling costs, the energy costs of communication infrastructure, raw materials and disposal costs and a host of other energy costs and environmental effects associated directly or indirectly with software systems.

Energy-aware software development is therefore only one aspect of Green IT; it is only concerned with the energy efficiency of software, that is, the energy costs directly attributable to how programs use the hardware during execution. The energy-aware software engineer cannot in general be aware of the whole Green IT field, which involves complex dependencies and tradeoffs and goes well beyond software engineering.

2.1. Environmental motivation

The energy consumed by ICT is growing both in absolute terms and as a proportion of the global energy consumption and thus plays an important role in meeting the targets of the Europe 2020 Agenda, which includes a goal to reduce greenhouse gas emissions by at least 20% compared to 1990 levels. Every device, from autonomous sensor systems operating at the milliwatt level to high-performance computing (HPC) systems and data centres requiring tens of megawatts for operation, consumes a certain amount of energy which results in the emission of CO₂.

As already pointed out, energy is consumed by hardware, but the software often causes a great deal of energy waste by inefficient use of the hardware. Increasing the energy efficiency of the software is at least as effective as development of more energy-efficient hardware. Furber remarks that “if you want an ultimate low-power system, then you have to worry about energy usage at every level in the system design” [1]. Furthermore, in many cases the energy efficiency of software has a direct positive effect on the efficiency of other energy-related aspects of systems. Obvious cases are cooling costs and battery costs—cooling requirements for data centres are directly related to the power dissipated by the computations, whereas for mobile systems, the number of battery replacements or recharges is similarly reduced if software is more energy efficient.

¹ <http://igsc.eecs.wsu.edu/> (formerly International Green Computing Conference (IGCC))

² <http://sameekhan.org/tagc/>

³ <http://www.cs.bris.ac.uk/Research/eaco/>

⁴ <http://greens.cs.vu.nl/>

⁵ <http://www.smartgreens.org/>

2.2. Strategic motivation

The energy efficiency of ICT systems plays a critical role in exploiting the massive amounts of information available in data centres and the full vision of the so-called Internet of Things. The power requirement of a data centre is typically measured in tens of megawatts, including cooling costs, while the Internet of Things generates increasing demand for a huge number of very low-power devices. The dream of “wireless sensors everywhere” is accompanied by the nightmare of battery replacement and disposal unless the energy requirements of software running on devices can be lowered to enable them to be powered by energy harvesters or RF power sources.

2.3. Development costs of energy-efficient software

In the current state of the art, development costs for energy-efficient systems are higher than for energy-wasteful systems due to the extra effort required to take energy consumption into account. This is a significant barrier to making energy efficiency a first-class design goal.

The motivations for research in energy-aware software development can thus be summarised as follows:

1. To lower the energy costs directly attributable to software execution, helping to reduce the environmental impact of ICT and to enable the next generation of ambient low-power devices.
2. To lower energy costs indirectly caused by software, such as the cost of cooling, power supplies, battery replacement and recharging.
3. To reduce the costs of the process of developing energy-efficient systems, by developing tools and techniques to assist the energy-aware developer.

3. Energy modelling

An energy model supporting software energy analysis associates energy consumption costs with basic program constructs such as source code blocks, basic blocks in the intermediate representation used during compilation or machine code instructions. In addition, other costs arising from the execution of a program may need to be considered, depending on the micro architectural features of the hardware; examples are costs associated with the memory hierarchy, such as the cost of a cache hit and miss or the cost of accessing on-chip and off-chip memory, and also costs associated with the processor pipeline, such as the cost of pipeline stalls. In addition, the cost of the processor being idle and the cost of processing multiple threads concurrently may also need to be considered.

An energy model, as understood in this chapter, is program independent. It captures the energy costs of basic software constructs in a given language executed on a given hardware platform. The model is used during program analysis (Section 3) to obtain information about the energy consumption of a given program.

The challenge in energy modelling for software energy analysis is in finding a good compromise between the accuracy of the model and the ease with which the information can be mapped onto software constructs. Regarding the former, model accuracy tends to be higher for models at the lower levels of abstraction, i.e. instruction-level energy models are typically more accurate than energy models at the intermediate representation of the compiler, and source code energy models are less accurate in comparison. However, understanding which source code lines or blocks consume most energy is much more useful to software developers looking to optimise their code for energy efficiency than knowing the energy consumed by the sequence of machine instructions issued by the compiler. The higher the level of abstraction at which the information is presented to the software developer, the easier it is for them to comprehend the impact of algorithms and coding on the energy consumed during program execution. Yet, taking measurements to characterise energy models is simplest and most accurate when performed at the lower levels of abstraction, where energy costs of low-level software constructs such as machine instructions can be determined directly.

3.1. Defining and constructing an energy model at ISA level

The instruction set architecture (ISA) is the interface between hardware and software. It defines the hardware architecture and its behaviour in terms of low-level programming constructs such as supported data types, machine instructions, registers, the memory architecture, any interrupt and exception handling as well as I/O operations. The ISA provides a practical level of abstraction for energy modelling, because it is possible to directly correlate the energy consumption of the hardware operations associated with instruction execution to low-level software constructs.

Energy modelling at ISA level dates back to 1994 when Tiwari et al. [6] first proposed a method to develop instruction-level power models for arbitrary processor architectures to estimate the power consumption caused by software. Such models could overcome the limitations of hardware design power analysis methods, which require access to gate-level design information including layout and tend to be impractically slow at producing results for system-level power analysis. Instruction-level power models, instead, are orders of magnitude faster at estimating the power consumption of embedded software and can achieve accuracy within 10% of what hardware design power analysis methods deliver. This is a worthwhile trade-off because software development involves numerous iterations during the coding phase, and rapid feedback of resource usage is critical for software developers to make energy-aware decisions.

The model in [36] captures the energy consumption directly associated with processing each instruction, obtained by measuring the average current drawn while executing a dedicated loop that only contains independent instances of the respective instruction to be profiled, multiplied by the supply voltage V_{CC} and further multiplied by the number and duration of the clock cycles required to execute the instruction. Variations in instruction base costs can be observed during measurements and are due to different operand values being used during execution. It was observed that different operand registers lead to negligible variation while using different immediate values, or different memory addresses lead to observable yet small

variation of no more than 5% for the architectures analysed. Because the exact operand values for instructions are only known at runtime, the energy model associates a single base cost with each instruction, representing averaged values. This is a very important feature of a single instruction cost Tiwari-style energy model as it has implications on the safety of the bounds inferred by worst-case static analysis techniques. This will be discussed further in Section 2.3.

Instruction base costs intentionally do not include any extra costs arising from executing an instruction within the context of other instructions, i.e. the overheads of executing arbitrary instruction sequences. One such cost is associated with switching the circuit state from executing one instruction to executing the next, termed the circuit state overhead. It captures the extra energy consumed due to switching on buses, e.g. as a consequence of changing opcodes and operand values, and using different functional units within the processor. The circuit state overhead is determined for all pairs of instructions by measuring loops that contain alternating sequences of the two instructions per pair. While including circuit state overheads into the energy model improves the accuracy of the model, the variation observed for individual instruction pairs was very limited for the architectures considered. It may thus be sufficient to determine a constant circuit state overhead cost and to use that instead of profiling all instruction pairs.

The execution of instruction sequences may give rise to other costs beyond the cost of circuit state switching, depending on the micro architecture of the processor. Resource contention due to data dependencies between instructions may cause pipeline stalls. Thus, the cost of pipeline stalls needs to be determined together with the number of stall cycles. In addition, there may be costs associated with cache misses, which typically cause execution delays of varying durations, depending on whether the fetch is from other cache levels of main memory. Their energy consumption also needs to be accounted for in an energy model, potentially sourcing information from a cache model that can provide cache miss rates for a given program. Thus, while instruction-level energy modelling techniques can be very accurate for simple architectures, the presence of complex architectural and micro architectural features such as several layers of caches, pipelines, superscalar processing, speculative execution, etc. can make it very difficult to achieve acceptable levels of accuracy when modelling at the instruction level.

In Ref. [7], this energy model is used to derive the energy consumption of a program *Prog* by Eq. 1:

$$E_{Prog} = \sum_i (B_i \times N_i) + \sum_{i,j} (O_{i,j} \times N_{i,j}) + \sum_k E_k \quad (1)$$

According to Eq. 1, the energy consumption of *Prog*, namely, E_{Prog} is calculated as the sum of three components: the base cost of instruction execution, the circuit state overhead and other inter-instruction effects. The first term in the sum in Eq. 1 represents the base cost, where B_i is the base cost of instruction i multiplied with the number of times i occurs in program *Prog*, N_i . The second term is the circuit state overhead, where $O_{i,j}$ represents the cost incurred by switching the circuit state of the processor from executing instruction i to executing instruction j . This is multiplied by the number of times instruction i is followed by instruction j during the

execution of program *Prog*, namely $N_{i,j}$. Finally, the third term in the sum accounts for the cost of k inter-instruction effects that may impact on software-related energy consumption, e.g. cache misses or pipeline stalls that can be characterised using external cache models or models of the micro architecture of the processor.

Equation 1 shows clearly the relation between the energy model and the analysis of the program. The terms B_i , $O_{i,j}$ and E_k are obtained from the energy model and are program independent. The terms N_i and $N_{i,j}$ are obtained by the analysis of the program, either dynamically, by profiling and counting the number of times each instruction or pair of instructions is executed, or statically as will be seen in Section 3.

Recently, instruction-level energy models have been developed for modern processors such as the Intel Xeon Phi, a many integrated core architecture for high-performance computing, and the hardware multi-threaded XMOS XCore embedded microprocessor [8].

The XMOS XCore instruction-level energy model [9] is based on the original model by Tiwari et al. However, it redefines the notion of base cost to be the power dissipated while the processor is idle and uses individual instruction costs, scaled by the level of concurrency in the processor's pipeline as well as a constant overhead to account for circuit state switching between instructions. Model characterisation was performed using a measurement setup and instruction loops similar to those originally proposed in Ref. [6]. The individual instruction costs represent averages over measurements obtained from running loops with instructions using operands that were generated pseudo-randomly, constraining values to those valid for the respective instruction. Evaluation of this multi-threaded instruction-level model showed average error margins of less than 7%. However, the model was designed to be used for static energy consumption analysis, requiring static analysis techniques to determine the number of idle cycles and the level of concurrent thread activity, in addition to the standard instruction stream statistics.

In contrast, the Xeon Phi instruction-level energy model [10] relies on performance counter statistics that are obtained at runtime, rather than through static analysis at compile time. This model is designed to be used with software profiling tools to support energy-efficient software development. The model is built by characterising the energy per instruction (EPI) of selected instruction types using microbenchmarks executed on different processor configurations in terms of numbers of cores and threads per core. Instructions are classified in terms of op-code and operand locations, both of which influence the EPI. The energy consumption of a given workload can then be determined by multiplying the runtime instruction statistics with the respective EPIs. This model achieves an average error rate of less than 5%.

Energy modelling at the ISA level gives us the following benefits: energy costs can be assigned at the instruction level, which is the same level as is output by the compiler; there are strong correlations between instruction properties and energy consumption, for example, the number of operands used in the instruction; and machine instructions can be related back to the original programming statements written by the software developer, as well as to various intermediate representations.

The construction of an energy model at the ISA level also has to address several challenges. Measurements need to be taken to determine both the base cost for each instruction and also the circuit state overhead. To achieve this, instructions are placed into infinite loops, i.e. loops of single instructions to obtain that instruction's base costs or loops of alternating instructions to characterise pair-wise circuit state overhead. The average current is measured while the loop is executed. Care needs to be taken to ensure the loop runs for a sufficiently long time to minimise measurement errors due to loop overheads. However, typically not all instructions can be directly profiled, requiring indirect or statistical approaches to their characterisation.

In general, for a modern processor with hundreds of instructions, the characterisation of the entire ISA is a significant effort. To reduce the measurement effort, rather than determining a base cost for each instruction, it may be sufficient to group instructions into classes of similar energy cost and to determine a single instruction class base cost. Likewise, instead of measuring circuit state overheads for individual instruction pairs, a cost that represents switching between instruction classes or a single constant circuit state overhead may be sufficient.

In addition, other properties such as the cost of running multiple threads and the cost of idle periods must be determined for multi-threaded architectures, and communication costs must be considered for interacting multi-threaded programs running on multicore platforms.

3.2. Energy modelling at higher levels of software abstraction

Instruction-level energy models are useful due to the close, almost direct link of measurements to programming constructs within the ISA. Energy models at higher levels of abstraction, however, provide more intuitive feedback to software and tool developers, albeit at the cost of accuracy of the predictions.

Modelling at the level of the intermediate representation (IR) used by compilers can be a useful compromise between the accuracy of a lower-level (ISA) model and the high-level source code. Since the compiler is a natural place for optimisation, modelling and predicting the energy consumption at IR level could therefore enable energy-specific optimisations.

IR-level energy models have been built using two distinct techniques. One is based on statistical methods and the other on mapping a lower-level model, i.e. one at ISA level, up to the IR level at compile time; both have been developed for LLVM IR [11] in the context of the LLVM toolchain [12].

In Ref. [13], statistical analysis has been employed to build an energy model for LLVM IR for the purpose of fast and accurate early-stage prediction of the energy consumption of embedded software at the function level to enable compile-time energy optimisation. Modelling starts with instrumenting and compiling the source code of a large set of benchmarks into architecture-independent LLVM IR to extract block-level statistics capturing the structural features of the source code in terms of LLVM instructions. Profiling of the LLVM IR basic blocks is then performed on a host computer to capture their dynamic behaviour in terms of basic block execution counts. The final step then factors in the timing and energy consumption of the target architecture. Using native compilation, back-annotation techniques to associate LLVM IR instructions with target machine instructions and statistical analysis, the target machine-

specific costs are associated with the architecture-independent LLVM IR. This requires a cost model of the instruction set for the respective target machine, which is assumed to be provided by the manufacturer. The resulting model can be used to estimate the energy consumption of code for the target hardware, based solely on its target-independent LLVM IR.

A mapping technique that lifts an energy model at ISA level to LLVM IR level is described in Ref.[14]. The energy characteristics of LLVM IR instructions are determined from the costs of the associated machine instructions based on a mapping that tracks which LLVM IR instructions created which machine instructions during the lowering phase of compilation, i.e. after optimisation passes.

The approach provides on-the-fly LLVM IR energy characterisation that takes into consideration the context of instructions since there is no program-independent mapping between ISA instructions and LLVM instructions. Strictly speaking, the energy model is still at the ISA level; a program-dependent mapping is used to obtain energy costs of LLVM IR instructions and blocks at compile time. The technique has been used for static energy consumption analysis at the LLVM IR level in Refs. [14, 15] and also in Ref. [16]. The accuracy of energy consumption estimation at LLVM IR level is typically within 1–3% of that achieved using ISA-level models. This indicates excellent potential for exploiting this energy transparency during code generation. In principle, the same mapping technique may be used to map the energy consumption of programs to even higher levels, such as source code blocks or functions.

An alternative approach to building a source-level energy model, used in [17] to obtain a source code energy model for Android code, is to identify basic energy-consuming operations from the source code and correlate them to energy costs by measuring energy consumption in a large number of benchmark programs and analysing the results using techniques based on regression analysis. The resulting energy model of the basic operations implicitly includes the effect of all the layers of the software stack down to the hardware, including compiled code, virtual machine and operating system layers. The approach is inherently approximate; nevertheless such an approach may be the only feasible one in cases where the software stack has many complex layers, rendering a mapping-based approach difficult or impossible.

3.3. The impact of data on the energy model

The classic instruction-level energy model as described in Section 2.1 does not capture the impact of data on software energy consumption. For instance, a single energy cost is assigned to each instruction or instruction type. In practice, however, energy consumption is dependent on the data being processed, and for simple processors, data can make a significant contribution to energy consumption. This is illustrated in **Figure 1**, which shows the dynamic power, in mW, for the single-cycle XMOS XCore bitwise AND instruction for all 65,536 combinations of 8-bit operands from 0 to 255. The colours in the “heatmap” range from dark blue, indicating low power, to dark red, indicating high power. In Ref. [18], 15% data-induced variation has been reported for the 8-bit AVR processor, while up to 1.7x data-dependent variation was observed for the 32-bit XMOS XCore in [19]. Variation of as much as 50% is reported in [19] for an ST20 32-bit microprocessor.

However, static resource consumption-bound analyses must provide bounds on resource consumption that are both safe and tight, i.e. sufficiently close to the actual values. A good example is worst-case execution time (WCET) analysis [20], where under-approximation is not acceptable, i.e. unsafe, and significant over-approximation is considered not useful. Thus, for bound analysis, models must support the derivation of safe and tight bounds. A key prerequisite to achieve this for WCET analysis is timing predictability within a system, which enables precise bounds to be established with acceptable effort, without sacrificing performance of the computation in the general case. In fact, the architecture of processors can significantly impact on the design of analysis tools and the properties of the analysis results these can deliver [21] in terms of safety and precision. This is equally important for static energy consumption analysis, i.e. predictable architectures enable precise models to be developed.

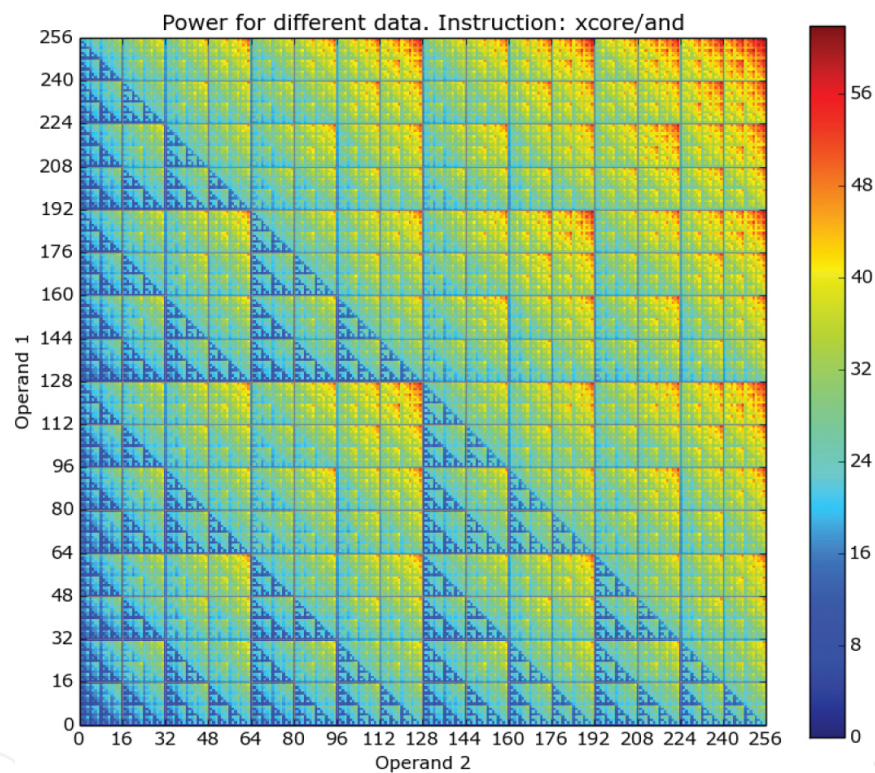


Figure 1. Dynamic power in milliwatts for the XMOS XCore AND instruction.

These observations naturally lead to the question of which energy cost should be associated with an instruction in a single-cost instruction-level energy model. Assigning the averages measured using randomly generated, valid data for the given instructions is a popular choice. Estimations based on such models may overpredict or underpredict the energy consumption of a program when compared to measurements. Error margins reported in the literature are typically below 10%, and overprediction and underprediction are both acceptable when the model is used to obtain estimations of energy consumption, and no guarantees are required.

It may be tempting to assign to an instruction the lowest or highest values observed during measurements to support best and worst-case analyses, respectively. However, this approach

has been shown to lead to high over-approximation [22] in worst-case energy consumption static analysis, so this may not be a suitable option. In fact, the estimations based on such models may never be reachable in practice. Intuitively, this is because the data that causes the highest energy consumption for one instruction is very unlikely to produce output that will trigger the highest energy consumption also in subsequent instructions.

This leads us to the question of which input data causes the worst energy consumption for a given program. This question is investigated in [23], where the problem of data-dependent energy consumption during program execution is formalised in terms of circuit switching and a formal proof is presented demonstrating that in general analysing switching in processor datapaths is NP-hard. Thus, optimal data-sensitive worst-case energy consumption analysis of programs is, in general, not achievable efficiently, and alternative approaches giving good approximations must be developed. This is an area of ongoing research.

In Ref. [18], energy modelling for worst-case energy consumption analysis has been explored. The most promising approach uses probabilistic energy distributions to characterise individual instruction pairs and proposes techniques to compose these to block-level instruction sequences. In Ref. [19], activity indices were introduced into a single-cost instruction-level model to achieve higher precision of energy consumption predictions and to enable bound analysis for architectures where data significantly impacts on energy consumption.

4. Static analysis of energy consumption

Static analysis is the other key component of energy transparency. Given an energy model assigning energy costs to some basic units of the program, the task of analysis is to determine the overall energy consumption of the program or the distribution of energy consumption over the parts of the program. Static analysis infers information about energy consumed by programs without actually running them, in contrast to dynamic analysis, which collects information about the program's behaviour while executing it. Here we consider only static analysis.

As with energy modelling, analysis can be performed on program representations at different levels in the software stack, ranging from source code (in different programming languages) through intermediate compiler representations down to ISA level and employing an appropriate energy model at that level.

4.1. Semantic representations of programs

Static analysis of a program, and in general any formal treatment of programs, requires reference to a semantic model of the program derived from the semantics of the programming language in which it is written. Several different semantic styles and notations are used, including denotational semantic, small-step or structured operational semantics and big-step or natural operational semantics. All of these can be applied to code at various levels such as source code, intermediate compiler representations or ISA.

A common representation language, suitable mainly for operational semantics, is constrained Horn clauses (CHCs), a subset of first-order logic which is widely used in software verification [24]. CHCs can represent code semantics at any level of abstraction. In this section we outline the key aspects of resource analysis using CHCs as a representation, but space does not allow a fully detailed presentation. More information can be found in the references given in the text.

A constrained Horn clause has the form $\forall x_0 \dots x_n (p_1(x_1) \wedge \dots \wedge p_n(x_n) \wedge \phi \rightarrow p_0(x_0))$. When representing program semantics, each predicate p_0, p_1, \dots, p_n typically corresponds to a program point, and its respective arguments x_0, x_1, \dots, x_n are tuples representing the state before and/or after those points. A clause thus represents a relationship between program states, and the constraint ϕ expresses the relationship between the values of the state variables. A special case of a Horn clause is where $n \leq 1$, that is, there is at most one atomic formula on the left of the clause. Such a clause often represents a transition from the state at one program point to the next.

Figure 2 illustrates the use of Horn clauses to represent an imperative program in a C-like language (a). The constrained Horn clauses (b) represent a transition system (c) induced by the program’s small-step operational semantics (the quantifiers in the Horn clauses are omitted). The predicates r_1, \dots, r_4 represent the program points 1, ..., 4 and $r_i(x_i)$ means that program point i is reachable with state x_i , where x_i is the tuple of variables in scope at that point.

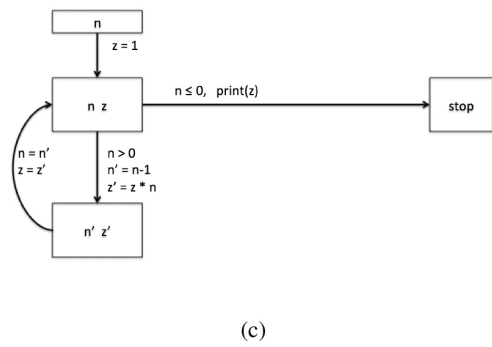
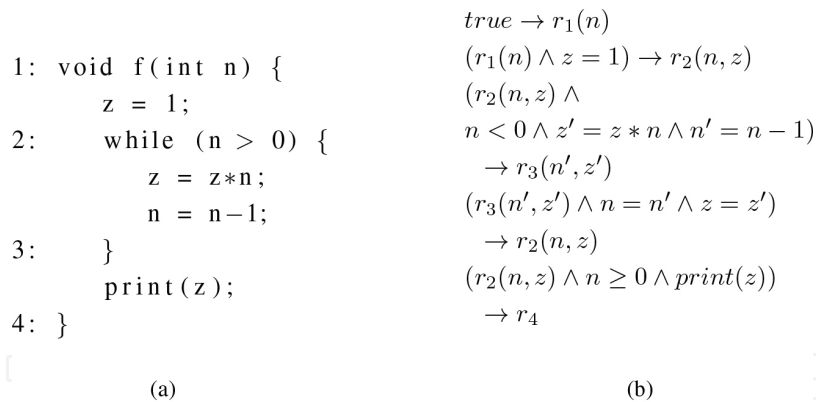


Figure 2. Transition system and constrained Horn clauses representing a program.

Lower-level programs such as ISA or intermediate code can be translated in a similar fashion, where typically each predicate represents a basic block in the code. Examples of the translation of XCore ISA programs to Horn clauses are given in Ref. [25]. Semantics-based methods for translating sequential imperative programs to Horn clauses are explained in Ref. [26]. Furthermore techniques for representing multi-threaded code as Horn clauses have been developed [27].

4.2. Techniques for energy analysis

Given such a representation of a program, techniques based on abstract interpretation [28] can derive safe approximations of program behaviour. In terms of CHCs, abstract interpretation can yield safe approximations of the values of the arguments of each predicate, which represent the set of possible states at some program point. A branch of abstract interpretation focuses on automatic complexity analysis, yielding complexity functions on the execution time of the program [29–33]. These techniques have been widely applied to analysis of Horn clauses and have been extended to analysis of energy and other resources [32, 33]. Tools, such as CiaoPP [34] and COSTA [35], have inbuilt facilities for resource analysis of programs including CHCs.

The essence of the techniques is to extract constraints from the Horn clauses representing the energy consumed. These constraints represent an abstraction of the behaviour of the program, in which the energy (or other resources being considered) can be considered as an implicit extra argument in the predicates of the Horn clauses (in some approaches, the extra-resource arguments are actually inserted into the Horn clauses, yielding a so-called “instrumented” representation). These constraints are then solved or approximated, to yield explicit formulas giving the consumption.

4.2.1. Linking analysis to an energy model

The Horn clauses in the semantic representation can be associated with energy values, using an energy model. For example, if the clauses are obtained from the source code, then each clause represents the execution of one statement or source code expression, and a corresponding source code energy model is associated with that clause. If the clauses are obtained from lower level code such as ISA, a clause typically represents the execution of an instruction or basic block; the corresponding energy consumption from the model can be mapped to the clause. The energy from a lower level model such as an ISA model can also be mapped to a Horn clause representing a higher level construct, possibly via an intermediate level as indicated in **Figure 3**.

Once this is done, constraints representing the energy consumption of the program are extracted from the Horn clause representation. To make the explanation more intuitive, we explain the process in terms of the transition system rather than the Horn clause representation. In the case of the loop at point 2, a recursive equation is obtained, e.g.:

$$cost_2(n) = e + cost_2(n-1) \text{ (if } n > 0), \text{ } cost_2(n) = 0 \text{ (if } n \leq 0) \quad (2)$$

where e is the energy cost of one iteration of the loop, obtained from the energy model. A dependency analysis also determines that the variable n is the relevant input parameter in this case. These equations can be solved to yield the expression giving the cost of the loop as a function of n , namely, $cost_2(n) = n * e$, and the cost of the whole program (a path from 1 to 4) is $cost(n) = e_1 + n * e + e_2$, where e_1, e_2 are the respective energy costs of the transitions before and after the loop.

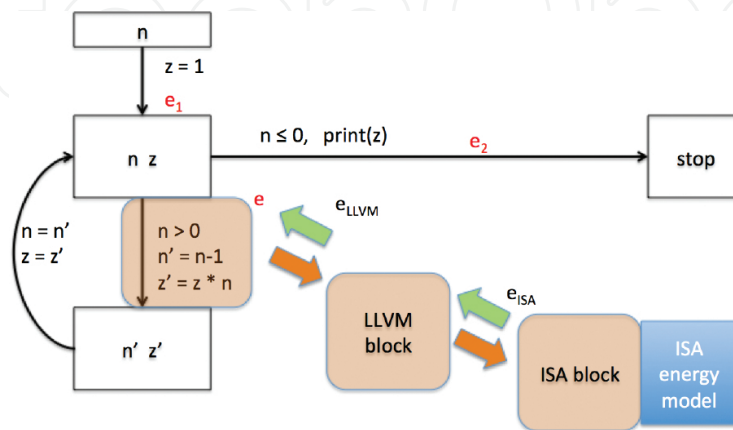


Figure 3. Combining an energy model with program analysis.

4.2.2. More complex analyses

The example shown is very simple, but the method generalises to more complex control and data structures. As the data and control-flow analysis of abstract interpretation is inherently approximate, the analysis in general gives safe upper and lower bounds on the number of times each part of the program is executed. This in turn gives upper and lower bounds on the energy consumed by the program. However, recall that the upper and lower bounds are also relative to the energy model, as discussed in Section 2.3. If the energy model supplies average costs for the basic instructions or operations, then the upper and lower bounds on the energy given by the analysis might not be safe, since the actual costs of executing the instructions might be respectively higher or lower than the average.

A further extension of the method of generating constraints and solving them yields static energy profiling [36], which shows the distribution of energy usage over the parts of the code, rather than a single function giving the total consumption of the program.

5. Software energy optimisation

One of the first works to stress the general importance of software energy efficiency, and identify aspects of software that affect energy consumption, was by Roy and Johnson [37]. More recent software-based approaches to achieving lower energy consumption are covered in [38, 39].

5.1. Computational efficiency

Firstly, there is a strong correlation between time and energy consumption for a given platform running a single computation thread. There are two reasons for this: less time means fewer instructions, and secondly when the task is finished, the processor can revert to a lower-power state for the excess time that a less efficient algorithm would use. The latter is called the “race to idle” in Ref. [39]. The correlation between time and energy is especially strong when asymptotic complexity is considered. It is highly likely, for example, that a single-threaded task that has $O(n^2)$ time consumption also has $O(n^2)$ energy consumption. Thus one of the main concerns of the energy-aware programmer, even with no knowledge of the energy consumption of the hardware, is to find computationally efficient algorithms and data structures suited to the task at hand.

5.2. Low-level or intermediate code optimisation

There is a range of techniques for low-level code energy optimisations, which could in principle be carried out by a compiler. These range from register allocation policies to avoid overheating a few intensively used registers, the use of very long instruction word (VLIW) instructions and vectorisation, to exploitation of low-power processor states using frequency and voltage scaling (DVFS). Note that such optimisations, in contrast to computational efficiency, are highly platform dependent and rely on a platform energy model expressed at the level of low-level code. Computational efficiency as described in Section 4.1 is also important in that low-level code optimisations are most effective when applied to frequently executed sections of code, such as tight inner loops, where a small saving in energy can make a significant difference to the overall computation.

Some energy optimisations rely on advanced compile-time (i.e. static) analysis. For example, knowledge of thread load imbalance and knowledge of predictable idle periods when processors can be put into low-power states are difficult to apply in the current compiler state of the art, since the analyses providing this knowledge are still emerging research areas.

5.3. Parallelism

The relationship between computational efficiency, time consumption and energy consumption is more complex for parallel than for sequential code. A multi-threaded solution using multiple cores can be more energy efficient than a single-threaded solution, even when the total amount of work done by the multi-threaded code is greater than that done by the single-threaded code. The savings are mainly due to the fact that the overall task time is reduced and so the processor(s) can revert sooner to a low-power state (the “race to idle” mentioned earlier).

Secondly, there can be energy savings if one or more cores can be run more slowly and still achieve the same overall task time as the sequential code. This is because power (P), frequency (f) and voltage (V) are related by the equation $P = cV^2f$ where c is a constant. Thus slowing down the processor (reducing f) saves power but not overall energy since the computation time is increased proportionally. However, a lower frequency is typically accompanied by a lower voltage, and the power/energy savings are quadratic in relation to voltage reduction.

5.4. Data and communication efficiency

Energy can be saved by minimising data movement. This can be achieved by writing software that reduces data movement using appropriate data structures, by understanding and exploiting the underlying system's memory hierarchy and by designing multi-threaded code that reduces the cost of communication among threads.

For example, the size of blocks read and written to memory and external storage can have a major impact on energy efficiency, while memory layout of compound data structures should match the intended usage in the algorithm, so that consecutively referenced data items are stored adjacently if possible. In multi-threaded code, consolidating all read-writes to or from disk to a single thread can reduce disk contention and consequent disk-head thrashing [39]. Furthermore, knowledge of the relative communication distances for inter-core communication can be used to place frequently communicating threads close to each other [40], thus reducing communication energy costs.

Synchronisation mechanisms can also have a serious impact on energy consumption. Waiting for events using polling loops is a notorious example as pointed out by Furber ("a polling loop [is] just burning power to do nothing") [1].

6. Software engineering activities and scenarios

We now look at energy-aware software from the designer's and developer's point of view. What are the activities that distinguish energy-aware design and development from standard approaches in which energy is considered at the end of the development process, if at all? In Section 5.1, we identify a number of generic activities that play an important role in energy-aware software engineering. In Section 5.2, we make the discussion a little more concrete by sketching scenarios in which these activities are applied.

6.1. Energy-aware software engineering activities

In this section we describe the most important activities involved in energy-aware software engineering. Some of these activities are extensions or modifications of conventional software engineering practices; others are new activities that only exist when energy efficiency is a design goal. **Figure 4** shows a number of activities and (some of) the interdependencies that arise in the context of different scenarios.

6.1.1. Specify application, including energy

The process of developing application software starts with a requirement specification that expresses not only *functional* properties, as in the classical approach, but also *non-functional* properties, including energy consumption and other resources. Classical methods for requirement specification need to be extended to allow non-functional specifications to be expressed.

Satisfying functional properties (in the sense of the classical concept of correctness with respect to a test suite or a formal input-output specification) is as important as doing so for non-

functional properties: an application that makes a device run out of batteries before a task is completed is as erroneous and useless as an application that does not compute the right result.

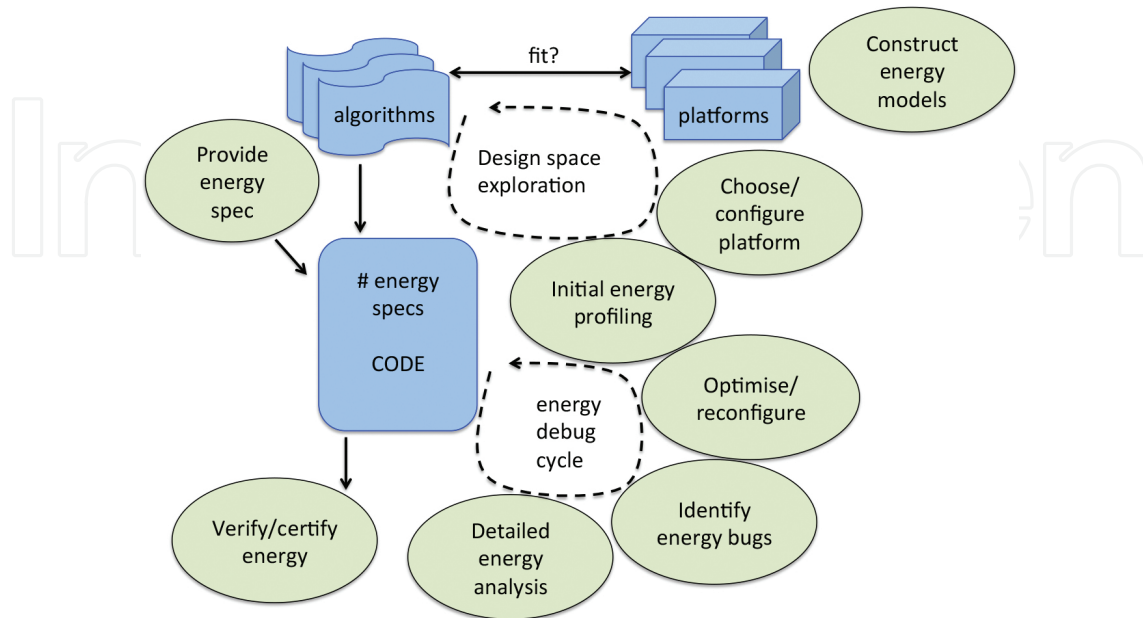


Figure 4. Energy-aware software engineering activities.

6.1.2. Construction of energy models

Creating energy models for different combinations of hardware platforms and programming languages is a part of the energy-aware development process. At one end of the spectrum, one might expect future hardware manufacturers to deliver an energy model for their instruction set architecture, and thus the model would be available “off the shelf.” At the other end, some projects might require the construction of an energy model specific to that project, perhaps because the hardware or software environment was not standard. In between these two extremes, energy modelling for energy-aware software development is becoming a more well-understood process.

6.1.3. Resource model of deployment platform

If energy efficiency is a design goal, we need to obtain an *energy model of the platform* on which the system is to be deployed (even though the software might be developed on a different platform).

Thus, obtaining the appropriate energy model is a vital task in energy-aware software engineering. Not only should an appropriate platform be selected, but its energy model should be available during software development to support other activities (see, e.g., Sections 5.1.6–5.1.9). We note also that several different energy models for a given platform might be selected, at different levels of abstraction suitable for different activities. For instance, high-level approximate models might be suitable for design space exploration (Section 5.1.6) and initial

energy profiling (Section 5.1.7), while more precise low-level models are needed for detailed energy analysis (Section 5.1.8) and optimisation (Section 5.1.10).

6.1.4. Selection of deployment platform

The choice of deployment platform itself might depend on its resource-usage model; thus, this activity and Section 5.1.3 are interdependent. By “platform” here is meant both the hardware and the software platforms; thus, the model should be capable of predicting the energy usage of software (in a given language and with a given runtime environment) being executed on a given piece of hardware.

6.1.5. Configure platform

Some platforms allow configuration that can have implications for energy consumption. Among such settings are clock frequency and voltage, the number of cores and the communication paths among them. At the software level, operating system settings can also be considered, such as the settings for power saving and the resolution of OS timer processes that can send interrupts to other processes.

6.1.6. Design space exploration

Choices taken early on in the design process can have a profound effect on the energy efficiency of the final result. *Design space exploration* as an energy-aware software development activity refers to the process of estimating energy implications of different possible design solutions, before they are implemented. It may involve especially activities such as selection of deployment platform (Section 5.1.4), platform configuration (Section 5.1.5) and initial energy profiling (Section 5.1.7). This involves energy modelling and analysis tools as in some other activities but with the difference that one is likely to be more satisfied with approximate models and thus rougher estimates of energy consumption rather than precise predictions.

6.1.7. Initial energy profiling

At early stages of energy-aware software design and implementation, tools are needed to perform an *initial energy analysis*. The purpose of this is to produce statically an *energy profile* that identifies the overall complexity of the energy consumption of the software and how energy consumption is distributed over the parts of the program. It could also at this stage identify energy bugs (parts of the application software that do not meet their energy consumption specification).

Initial energy analysis requires an *energy model* of the deployment platform at an appropriate level of abstraction. At early stages, parts of the software may be missing, and it might not be possible to compile it to machine instructions; thus, an approximate model based on a model of source code might have to suffice.

6.1.8. Detailed energy analysis

During more advanced stages of energy-aware software implementation, detailed energy analyses at finer levels of granularity are needed. These are provided by tools containing more precise low-level energy models of the platform, able to give precise estimates of the energy consumption of critical parts of the code, which could be targets for energy optimisation.

6.1.9. Identify energy bugs

Energy bugs occur when software does not conform to an energy specification. The specification might state some overall resource requirement in which energy consumption is implicit, for example, on the length of battery life. The bug in such a case could be some energy-consuming process that is more expensive than necessary, a service that is not switched off when required, threads that synchronise badly and spend too much time waiting and so on.

6.1.10. Energy optimisation or reconfiguring

The broad concept of energy optimisation is applied throughout the whole software engineering process and starts right at the beginning with design space exploration and selection of appropriate platform, algorithms and data structures.

The specific energy optimisation performed in this activity is driven by the detailed energy analysis and the energy model of the platform. Both manual and automatic optimisations can be applied; the energy analysis should point to the sections of code that use the most energy, either because they involve costly energy operations or because they are frequently executed (e.g., tight inner loops). This activity also includes application of energy-optimising compilers.

6.1.11. Verify or certify energy consumption

Energy-critical applications need to be certified with respect to an energy specification. Tools combining detailed energy models and precise energy analysis are required in order to compare the inferred energy consumption with the specification, either verifying conformance or certifying that it holds within some specified limits of behaviour such as input ranges.

6.2. Energy-aware software engineering scenarios

In this section, we sketch scenarios in which the activities described in the previous section are applied.

6.2.1. Embedded system development on xCORE

The ENTRA project⁶ considered energy analysis of embedded systems implemented in the XC language and deployed on the xCORE multicore architecture. An energy-aware software development strategy for such applications involves the following energy-aware activities:

⁶ <http://entraproject.eu>

- Energy specification by writing pragma comments in the XC source code. Such pragmas could express energy constraints derived from customer requirements on the power supply.
- Platform selection and configuration. The xCORE architecture is highly configurable both in terms of the number of cores and their interconnection. The choice and configuration are guided by an energy model applied to proposed solutions, taking into account thread communication energy costs in a given configuration, as described in more detail in [40].
- Detailed program-independent energy models of the platform at ISA level are available. Program-dependent energy models are obtained for XC and LLVM IR code for the application from the ISA model and used to perform more precise and detailed energy analysis of the application.
- Optimisations of expensive or frequently executed code is performed on the basis of the energy analysis.
- The energy-optimising compiler for XC is applied to the application.
- Pragmas in the code are verified using comparison of the energy consumption predicted by the analysis with the constraints in the specification.

6.2.2. Android app development

A case study on Android app energy optimisation was carried out [41]. The study involved energy modelling and optimisation of applications based on an established game engine. An energy specification was not given; the aim of the study was to use a source code-level energy model to identify the most energy-intensive parts of the code in a number of typical use cases and then apply manual optimisations, reducing energy usage directly and thus prolonging battery life.

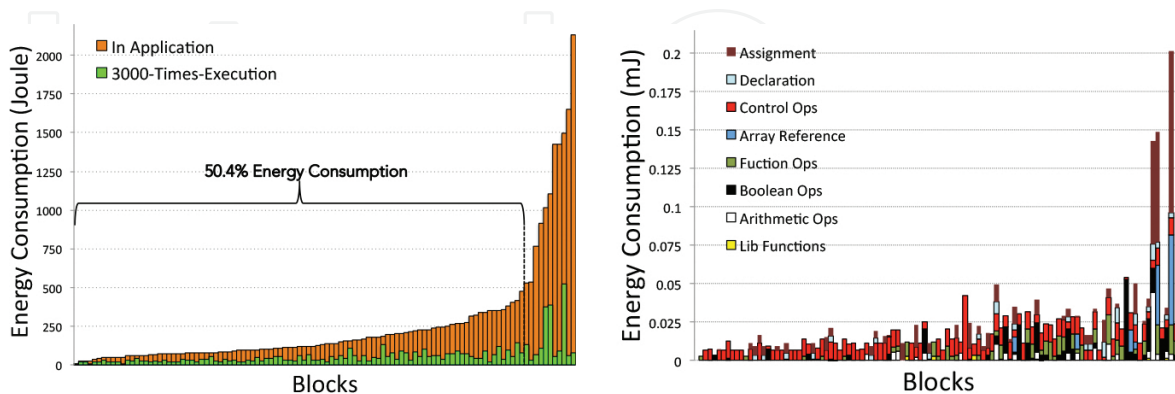


Figure 5. Energy distribution over basic blocks in an Android application. Blocks are sorted by the order of their contribution to runtime energy costs. The *green bars* indicate the relative costs of the blocks.

Energy-aware software engineering activities included:

- Building a fine-grained source code energy model by regression analysis from energy measurements on the target hardware and Android software platform of a set of test cases exercising the functions of the underlying game engine.
- Dynamic profiling of the code, which provided an energy profile that allowed the most energy-expensive basic blocks to be identified. For example, **Figure 5** from Ref. [41] shows an example of how the relative energy cost of basic source code blocks enable the programmer to focus optimisation effort on the most energy-consuming blocks.
- Manual refactoring of the source code, targeted at the most expensive blocks, which succeeded in increasing energy efficiency by a factor of 6–50% in various use-case scenarios.

7. Summary

The purpose of this chapter was to motivate energy-aware software engineering and to outline the principles and methods underlying it. We discussed why it is worth focusing on energy efficiency during software development and why energy efficiency should be a first-class software design goal.

A key concept is energy transparency, which makes the energy consumption of a program explicit at the level of code, rather than at the level of hardware, where the energy is actually consumed. A substantial part of the chapter described the two main fields of study relevant to energy transparency, namely, energy modelling and static analysis. Energy transparency is achieved by analysis of a program with respect to an energy model. The model associates energy consumption costs with basic units of the software, such as instructions or statements, and includes also other costs and overheads. Static analysis for energy consumption is a semantics-based formal technique, extending methods for automatic complexity analysis of programs, which is a branch of abstract interpretation.

The last part of the chapter considered the various features of software that can affect energy consumption. An energy-aware developer can use energy transparency to focus energy-aware design and optimisation in the most effective way. The field of energy-aware software engineering is only just emerging, and we described a number of activities that characterise energy-aware software engineering, extending or modifying conventional practices. The chapter concluded with a description of two short scenarios of energy-aware software engineering; however, a great deal of further experience and tool development is needed to realise the full vision.

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