Usuba

Optimizing & Trustworthy Bitslicing Compiler

Darius Mercadier Pierre-Évariste Dagand Lionel Lacassagne Gilles Muller
firstname.name@lip6.fr
Sorbonne Université, CNRS, Inria, LIP6, F-75005 Paris, France

Abstract

Bitslicing is a programming technique commonly used in cryptography that consists in implementing a combinational circuit in software. It results in a massively parallel program immune to cache-timing attacks by design.

However, writing a program in bitsliced form requires extreme minutia. This paper introduces Usuba, a synchronous dataflow language producing bitsliced C code. Usuba is both a domain-specific language – providing syntactic support for the implementation of cryptographic algorithms – as well as a domain-specific compiler – taking advantage of well-defined semantics invariants to perform various optimizations before handing the generated code to an (optimizing) C compiler.

On the Data Encryption Standard (DES) algorithm, we show that Usuba outperforms a reference, hand-tuned implementation by 15% (using Intel's 64 bits general-purpose registers and depending on the underlying C compiler) whilst our implementation also transparently supports modern SIMD extensions (SSE, AVX, AVX-512), other architectures (ARM Neon, IBM Altivec) as well as multicore processors through an OpenMP backend.

1 Introduction

Most symmetric cryptographic algorithms rely on *S-boxes* to implement non-linear (yet reversible) transformations that obscure the relationship between the key and the cyphertext. For example, the third *S-box* of the Serpent cipher [2] takes 4 bits of input and produces 4 bits of output. To implement this *S-box* in C, we would typically write:

```
int SBox3 = {  8, 6,  7, 9, 3, 12, 10, 15,
              13, 1, 14, 4, 0, 11,  5, 2  };
int lookup( int index, int[] sbox ) {
    return sbox[index & 0b1111];
}
```


WPMVP'18 , February 24–28, 2018, Vienna, Austria

ACM ISBN 978-1-4503-5646-6/18/02…$15.00
https://doi.org/10.1145/3178433.3178437

For example, on input $\texttt{0110}_\text{b} = 6_\text{d}$, this function returns the seventh (note the 0-indexing) element of the table, which is $10_\text{d} = \texttt{1010}_\text{b}$.

This implementation suffers from two problems. First, it wastes register space: a priori, the input will consume a register of at least 32 bits, leaving 28 bits unused, which means that the full potential of the CPU is not exploited. Second, it is vulnerable to cache-timing attacks [5]: due to cache effects, repeated data-dependent access to a lookup table can leak information on the data being encrypted.

However, it is possible, for example using Karnaugh maps, to compute a logical circuit that implements such a function. The resulting circuit will – by construction – run in constant time regardless of the inputs. For instance, the third *S-box* of Serpent amounts to the following circuit

```
node sbox (a,b,c,d:bool) return (w,x,y,z:bool)
vars t01,t02,t03,t04,t05,t06,t07,
     t08,t09,t10,t11,t12,t13,t14: bool
let
 t01 = a | c;     t02 = a ^ b;     t03 = d ^ t01;
 w   = t02 ^ t03; t05 = c ^ w;     t06 = b ^ t05;
 t07 = b | t05;   t08 = t01 & t06; t09 = t03 ^ t07;
 t10 = t02 | t09; x   = t10 ^ t08; t12 = a | d;
 t13 = t09 ^ x;   t14 = b ^ t13;   z   = ~t09;
                  y   = t12 ^ t14;
tel
```

where the four inputs are `a`, `b`, `c` and `d`, the four outputs are `w`, `x`, `y` and `z`, and the remaining variables are temporaries. Seen as a software artefact, it amounts to a function of type $\texttt{bool}^4 \rightarrow \texttt{bool}^4$: given an input of 4 Booleans, it computes 4 Booleans corresponding to the output of the *S-box*. For instance, feeding this circuit with $(\texttt{0},\texttt{1},\texttt{1},\texttt{0}) = \texttt{0110}_\text{b} = 6_\text{d}$, will produce the outputs $(\texttt{1},\texttt{0},\texttt{1},\texttt{0}) = \texttt{1010}_\text{b} = 10_\text{d}$, as before. Here, only variables of Boolean type are used, but the same program could manipulate `uint64_t` values. Conceptually, this would amount to executing 64 such circuits in parallel: one circuit applied to the bits of rank 0 of the registers, another to the bits of rank 1, *etc.* This works because only bitwise operations are used (`AND`, `OR`, `XOR` and `NOT`), which means that the bits of each rank of the registers are independently modified.

Bitslicing consists in reducing an algorithm to bitwise operations (`AND`, `OR`, `XOR`, `NOT`, *etc.*), at which point we can run the algorithm with bit-level parallelism, viewing a n-bits register as n 1-bit registers, and a bitwise `AND` as n-parallel `AND` operators. To execute such circuit, the inputs must be

converted: the i-th bit of the j-th input become the j-th bit of the i-th register. This operation amounts to a matrix transposition transforming n m-bit inputs into m n-bit registers.

Bitslicing is thus able to increase performance by exploiting data-parallelism, while improving security by disabling cache-timing attacks. Historically, bitslicing is a manual process. For instance, here is a snippet of a bitsliced implementation of the Data Encryption Standard (DES) by Kwan [17]:

```
s1 (r31^k[47], r0^k[11], r1^k[26], r2^k[3],
  r3^k[13], r4^k[41], &l8, &l16, &l22, &l30);
s2 (r3^k[27], r4^k[6], r5^k[54], r6^k[48],
  r7^k[39], r8^k[19], &l12, &l27, &l1, &l17);
s3 (r7^k[53], r8^k[25], r9^k[33], r10^k[34],
  r11^k[17], r12^k[5], &l23, &l15, &l29, &l5);
```

The full implementation consists of hundreds of lines in the same, tedious style. Debugging and maintaining such code is hard at best, and optimizing it even more so. Furthermore, this code shows its age by failing to exploit modern vector extensions.

Observing that a bitsliced algorithm is fundamentally a circuit written in software, we designed Usuba, a synchronous dataflow programming language for implementing circuits in software. This paper makes the following contributions:

- We have designed Usuba, a synchronous dataflow language targeting cryptographical and high-performance applications. While its syntax and semantics (Section 2) are inspired by Lustre [13], it has been specialized to address cryptographical needs (lookup tables, permutations, binary tuples, arrays).
- We have implemented a compiler, `Usubac`, from Usuba to C (Section 3). It applies standard dataflow compilation techniques [6] as well as domain-specific transformations, such as handling bitvectors, expanding permutations and lookup tables.
- We have implemented several optimizations (Section 4). This includes standard transformations such as inlining, constant folding, common subexpression elimination (CSE) and copy propagation, as well as a domain-specific instruction scheduling algorithm. The latter is tailored to handle the unusual structure of our programs (large number of live variables, absence of control structures), for which C compilers have a hard time generating efficient code.
- We evaluate the end-to-end performance of an Usuba program, namely DES, on several SIMD architectures and measure the impact of our optimizations (Section 5). At equivalent word size, our Usuba implementation is 15% faster than a functionally-equivalent, hand-tuned implementation of DES [17]. Besides, the same Usuba program can also be compiled to manipulate larger wordsizes (such as those offered by the AVX-512 extensions), yielding a 350% improvement over the hand-tuned, fixed wordsize implementation.

$$
\begin{array}{rcl}
\langle \text{nd} \rangle & ::= & \texttt{node}\ f\ (\langle \text{tv} \rangle^+)\ \texttt{returns}\ (\langle \text{tv} \rangle^+) \\
 & & \texttt{vars}\ \langle \text{tv} \rangle^+\ \ \texttt{let}\ \langle \text{eqs} \rangle\ \texttt{tel} \\
\langle \text{tv} \rangle & ::= & x : \langle \text{typ} \rangle \\
\langle \text{typ} \rangle & ::= & \texttt{bool} \mid \langle \text{typ} \rangle \texttt{[n]} \\
\langle \text{eqs} \rangle & ::= & \langle \text{eq} \rangle \mid \langle \text{eqs} \rangle ; \langle \text{eqs} \rangle \\
\langle \text{eq} \rangle & ::= & \langle \text{lhs} \rangle = \langle \text{expr} \rangle \\
 & \mid & \texttt{forall}\ i\ \texttt{in}\ [\langle \text{aexpr} \rangle, \langle \text{aexpr} \rangle], \langle \text{eqs} \rangle \\
\langle \text{lhs} \rangle & ::= & \langle \text{var} \rangle \mid (\langle \text{var} \rangle\ \langle \text{var} \rangle^+) \\
\langle \text{var} \rangle & ::= & x \mid x[\langle \text{aexpr} \rangle^+] \\
 & \mid & x[\langle \text{aexpr} \rangle ... \langle \text{aexpr} \rangle] \\
\langle \text{expr} \rangle & ::= & x \mid \texttt{n} \mid (\langle \text{expr} \rangle \langle \text{expr} \rangle^+) \\
 & \mid & \langle \text{unop} \rangle \langle \text{expr} \rangle \mid \langle \text{expr} \rangle\ \langle \text{binop} \rangle\ \langle \text{expr} \rangle \\
 & \mid & f(\langle \text{expr} \rangle^+) \\
\langle \text{unop} \rangle & ::= & \texttt{~} \qquad \langle \text{binop} \rangle ::= \texttt{\&} \mid \texttt{|} \mid \texttt{\^{}} \\
\langle \text{aexpr} \rangle & ::= & i \mid \texttt{n} \mid \langle \text{aexpr} \rangle\ \langle \text{abinop} \rangle\ \langle \text{aexpr} \rangle \\
\langle \text{abinop} \rangle & ::= & \texttt{+} \mid \texttt{-} \mid \texttt{/} \mid \texttt{\%}
\end{array}
$$

Figure 1. Usuba grammar

Usuba is also trustworthy: we apply translation validation [21] whereby each run of the compiler is followed by a verification pass that checks the semantics equivalence of the source program with the generated code. The same mechanism can also be used to validate an optimized Usuba program (provided by the user) with respect to a naive Usuba implementation (playing the role of a specification, also provided by the user). We shall not dwell on these techniques in the present paper, the description of the formal semantics and the evaluation of the verification framework being beyond the scope of the workshop.

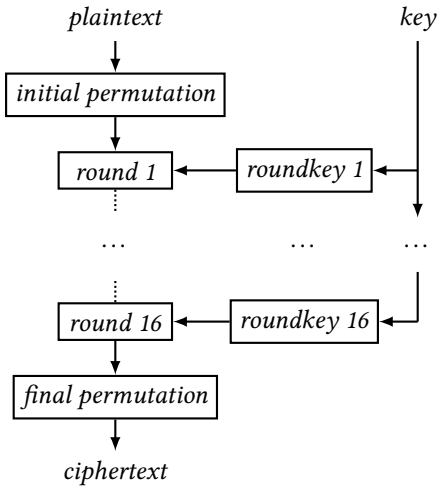
2 Usuba

Usuba is a synchronous dataflow language akin to a hardware description language (HDL). It enables the concise and high-level description of *software circuits* that are then compiled into a bitsliced implementation. The benefits of Usuba are twofold. First and by design, any software circuit specified in Usuba admits a bitsliced (and therefore efficient) implementation. Second, the informal description of symmetric cryptographical algorithms (by means of pseudo-circuits, such as in Menezes et al. [19]) directly translates into Usuba's formalism: as a result, one can effectively reason about and then run the specification. In this section, we present the syntax and semantics of Usuba.

2.1 Syntax

An Usuba program is composed of a list of *node declarations*, *permutations* and *lookup tables*.

Nodes correspond to the encapsulating blocks in circuit diagrams. A node (Fig. 1, ⟨nd⟩) specifies its input, output and lexical typed variables as well as a list of equations ⟨eqs⟩. Types ⟨typ⟩ can be Booleans or arrays of size n (for a fixed $n \in \mathbb{N}^*$, known at compile-time). For convenience, we also



(a) Informal specification [19, p.254]

```
node des (plaintext: u64, key: u64)
     returns (ciphered: u64)
vars des: u64[17], left: u32, right: u32
let
  // Initial permutation
  des[0] = init_p(plaintext);
  // 16 rounds
  forall i in [1,16] {
    des[i] = des_round(des[i-1], roundkey[i-1](key));
  }
  // Final permutation
  (left,right) = des[16];
  ciphered = final_p(right,left)
tel
```

(b) Usuba implementation

Figure 2. DES encryption algorithm

offer a type u*n*, which (concisely) stands for `bool[n]`. An equation ⟨eq⟩ is either a single assignment or a quantified (but statically bounded) definition of a group of equations. A formal variable ⟨var⟩ is either the identifier of a variable, some elements of an array (*e.g.*, `x[2, 4, 7]` or even `x[3]`) or a contiguous slice of an array (*e.g.*, `x[2..7]`). Expressions ⟨expr⟩ are either variables, unsigned integer constants, tuples, unary or binary bitwise operations or node calls. Unary and binary operators (⟨unop⟩ and ⟨binop⟩) correspond exactly to the corresponding C operators. Arithmetic expressions ⟨aexpr⟩ are evaluated at *compile time* when a group of equations (defined by a `forall`) is unfolded into a sequence of standard equations. An arithmetic expression is thus either an unsigned integer constant, a variable introduced by an enclosing `forall` or an arithmetic operation between two arithmetic expressions.

Figure 2 shows both the textbook description of the DES encryption algorithm and its (almost literal) translation in Usuba. DES takes two inputs, a 64 bit block of plaintext and a 64 bit key, applies an initial permutation (encapsulated in a node `initial_p`) to the plaintext, followed by 16 rounds (encapsulated in a node `des_round`) that take as input the round key and the output of the previous round, concluding with a final permutation (encapsulated in a node `final_p`) that produces the ciphertext. An Usuba program can thus be understood as a merely textual representation of a dataflow graph.

Permutations are commonly used in cryptographic algorithm to provide diffusion. Usuba offers syntactic support for declaring permutations. For instance, the initial permutation of DES amounts to the following declaration specifying which bit of the input bitvector should be routed to the corresponding position of the output bitvector:

```
perm init_p (input:u64) returns (out:u64) {
   58, 50, 42, 34, 26, 18, 10,  2, 60, 52, 44, 36, 28,
   20, 12,  4, 62, 54, 46, 38, 30, 22, 14,  6, 64, 56,
   48, 40, 32, 24, 16,  8, 57, 49, 41, 33, 25, 17,  9,
   1 , 59, 51, 43, 35, 27, 19, 11,  3, 61, 53, 45, 37,
   29, 21, 13,  5, 63, 55, 47, 39, 31, 23, 15,  7  }
```

The direct bitsliced translation of this permutation is a function of 64 Boolean inputs and 64 Boolean outputs, which consists of simple assignments. After copy propagation, a permutation is thus no more than a (static) renaming of variables.

Lookup tables are, in particular, used to specify *S-boxes*. The first S-box of DES is thus specified by:

```
table sbox_1 (input:u6) returns (out:u4) {
  14,  0,  4, 15, 13,  7,  1,  4,  2, 14, 15, 2, 11,
  13,  8,  1,  3, 10, 10,  6,  6, 12, 12, 11, 5,  9,
   9,  5,  0,  3,  7,  8,  4, 15, 1, 12, 14, 8,  8,
   2, 13,  4,  6,  9,  2,  1, 11,  7, 15,  5, 12, 11,
   9,  3,  7, 14,  3, 10, 10,  0,  5,  6,  0, 13  }
```

The input $000111_b = 7_d$ produces the output $000100_b = 4_d$, which is the 8th element of the array. Such a declaration is then converted to a circuit by either looking up a database of known circuits or, failing to find one, compiling it using binary decision diagrams (BDDs).

2.2 Static & dynamic semantics

Usuba is a statically-typed synchronous dataflow language. Its type and clock system are unsurprising and largely borrowed from earlier synchronous languages, such as Lustre [13]. We refer to Biernacki et al. [6] for a formal as well as algorithmic presentation of type and clock checking. Our treatment of arrays is reminiscent of LustreV4 arrays, which

were coincidentally introduced as part of an effort to compile Lustre programs to hardware circuits.

From a semantics standpoint, an Usuba program textually embodies a dataflow graph: an unordered set of equations declaratively describe the "wiring" from input variables to output variables. For instance, the following Usuba programs, which contains the same equations in a different order, are semantically equivalent:

```
x1 = ~a.4;                x4 = x3 ^ x2;
x2 = ~a.1;          ≅     x2 = ~a.1;
x3 = a.4 ^ a.3;           x1 = ~a.4;
x4 = x3 ^ x2;             x3 = a.4 ^ a.3;
```

This equational approach offers *referential transparency*: any subterm of the program can be hoisted as a new equation with a fresh variable and the subterm replaced by that variable. The compiler backend eventually produces a valid scheduling, which consists in finding an ordering of the equations for which sequential execution of the instructions preserves the intended semantics. These particularities of the dataflow model make it extremely convenient for implementing and proving the correctness of compilation passes: new equations can be introduced at any point, term can be inlined or hoisted, and the scheduling pass eventually takes care of ordering them so as to generate efficient code.

As a result of our design, every Usuba program can be compiled to an efficient bitsliced C program. The resulting imperative code is immune to cache-timing attacks since it *cannot* perform any input-dependent access to memory.

3 Compilation

This section presents Usuba's compiler, `Usubac`, and the generation of C from Usuba. Usuba programs are first simplified to a proper subset of Usuba (Section 3.1). Several optimizations are then applied on the program (Section 4), before generating C code (Section 3.2).

3.1 Usuba0

The high-level constructs offered by Usuba boil down to a strict subset of the language, which we call Usuba0. Usuba0 can be understood as a core calculus for bitsliced algorithms (from a foundational perspective) or as a dataflow assembly language amenable to bitslicing (from a practical perspective). In Usuba0, variables are only of Boolean type. Equations assign a single variable, unless they perform a function call in which case they assign a fully-expanded tuple of Boolean variables. Expressions consist only of bitwise operations and the only constants are of Boolean type, *i.e.* 1 and 0. The front-end of the Usuba compiler transforms Usuba programs into (semantically-equivalent) Usuba0 programs by converting lookup tables to boolean circuits, unfolding array definitions, expanding non-Boolean constants, and inlining permutation tables, operators and tuples. The resulting Usuba0 program can then be optimized (Section 4) and eventually compiled to C (Section 3.2).

3.2 Generation of C code

Generating C code from Usuba0 is straightforward, assuming that the equations have been scheduled according to their data-dependencies. Each node is compiled into a function, with return values passed by pointers. Booleans are transformed to either `int` or vector types (depending on the underlying architecture). Equations are converted into assignments. Expressions are translated to the corresponding C expressions. Function calls are converted to standard C function calls, where the left-hand side of the equation is passed by reference to the function. Generating C code targeting a specific SIMD extension, such as Intel's SSE, AVX and AVX-512, ARM's Neon or IBM's AltiVec, only requires using the bitwise instructions specific to the vector extension, and embedding in the runtime an efficient transposition algorithm adapted to the architecture.

4 Optimizations

Cryptographic applications put high requirements on the performance of the generated code. The C compiler will optimize the code produced by Usuba but our experiments have shown that some optimizations produce better results when done by Usuba's compiler itself. This is due to the unusual structure of our code: bitsliced programs tend to exhibit hundreds of live variables at any point, which is much more than what C compilers are used to deal with. Optimizing Usuba0 code offers several advantages. Variables are assigned only once and there is no control structure, which means that the code is in single static assignment (SSA) form with no φ node. Moreover, information from the original Usuba program is still available, which can be exploited to guide instruction scheduling for example.

This section describes our optimizations and their impact on the performance of the DES implementation presented in Section 2.1. The C compilers we used are `Clang` 3.8.0, `ICC` 17.0.2 and `GCC` 5.4.0. The measurement were carried on an `Ubuntu 16.04` machine with a CPU `Intel Core i5-6500` (3.20 GHz). Unless specified otherwise, the flags passed to the C compilers are `-march=native -O3`. We compare our implementation with Kwan [17]'s bitsliced implementation of DES for 64 bits registers. We refer to it as *manual implementation* or *Kwan's implementation*.

Constant folding Recall that the only operations left in Usuba0 are bitwise operations, function calls and binary constants. Bitwise operations involving constants are simplified, following standard Boolean algebra. Doing this optimization in Usuba produces slightly smaller C files, and guarantees that they are performed, irrespective of the level of optimization at which the C code is compiled.

Common subexpression elimination and copy propagation (CSE-CP) Common subexpression elimination consists in replacing several instances of the same expression by a temporary variable holding the result of this expression. Similarly, copy propagation aims at avoiding useless

CC	without	with	speedup
Clang	1.23	1.36	× 1.11
ICC	1.17	1.35	× 1.15
GCC	1.00	1.07	× 1.07

(a) CSE-CP

	inlining	speedup	code size (B)
(1)	Usuba	× 2.14	91544
(2)	Clang	× 1.13	91576
(3)	without	× 1.00	87480

(b) Inlining

CC	without	with	speedup
ICC	1.08	1.41	× 1.31
Clang	1.12	1.26	× 1.13
GCC	1.00	1.11	× 1.11

(c) Scheduling

CC	without	with	speedup
ICC	1.26	1.41	× 1.12
Clang	1.16	1.40	× 1.21
GCC	1.00	1.01	× 1.01

(d) Explicit spilling

Table 1. Normalized performance impact of the optimization passes

assignments by removing direct assignments `x = y` (where `x` and `y` are both variables) and using `y` instead of `x` in the subsequent expressions. This optimization is essential since a powerful feature of Usuba is the ability to do tuple assignments to split arrays (like `(left,right) = des[16]` in DES's code, Figure 2), that are then compiled away by the copy propagation.

Table 1a compares the effect of performing the CSE-CP in Usubac with the effect of letting the C compiler do it. The tests were done on DES, and the results have been normalized with GCC's throughput without CSE-CP equal to 1. At `-O3` optimization level, the C compilers perform CSE-CP, but doing it in Usuba increases throughput by 7 to 15%. We conjecture that the C compilers are unable to detect the commonalities due to the sheer amount of code produced.

Inlining Inlining enables further optimizations, as it may open opportunities for more CSE or copy propagation. Also, it saves the need to push and pop arguments on the stack, which has a significant impact when dealing with function with many parameters. Unlike C compilers, Usuba agressively inlines every function, exploiting the fact that sidestepping the call-stack outweighs the cost of executing a larger binary. The user is granted additional control through the Usuba attributes `_inline` and `_no_inline`, which can be used to manually force a node to be inlined or not.

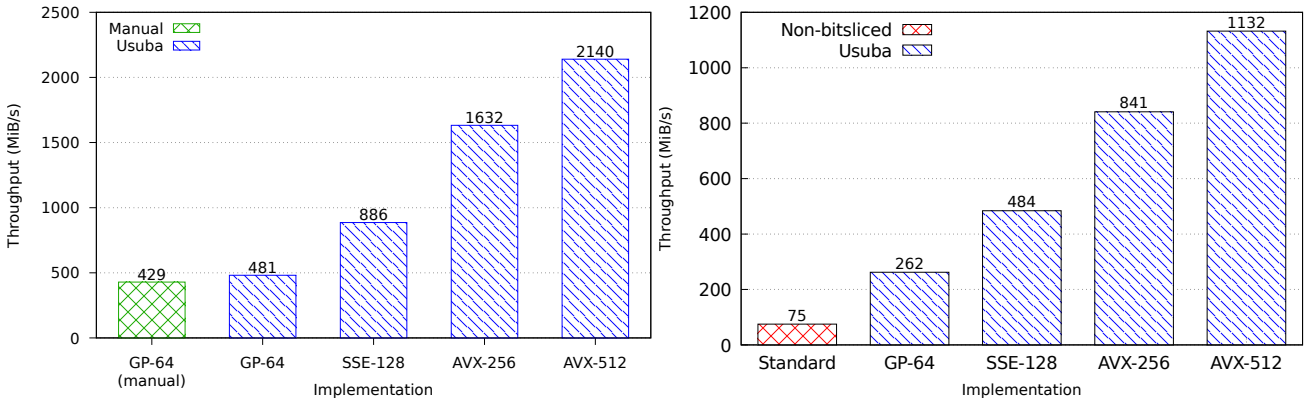
Table 1b shows the effect of inlining on DES's code: it compares the code without inlining ((3), "without") from neither Usuba nor Clang, with Clang's inlining ((2), "Clang") and with Usuba's inlining ((1), "Usuba"). In all cases, constant folding and CSE are active. Without any inlining done by Usubac (3), Clang chooses to only inline the S-boxes (2), thus gaining 10% performance, but fails to inline the round function. However, Usubac inlines every functions, thus increasing the throughput by more than 110% (2). This is mainly due to the fact that the round function takes in and returns a lot of variables, which causes unnecessary assignments through the stack. The code without inlining is not the smallest, as shown in column "Code size", because it contains the round function and the numerous assignments related to its arguments.

Scheduling Usually, C compilers do a good job at scheduling instructions. However, Usuba0's code has an unusual structure as it is organized in chunks of instructions, each chunk originating from the unfolding of tuples. For example, the Usuba operation `x = a & b` – where `x`, `a` and `b` are of type `u64` – normalizes to 64 `AND` instructions, but the 64 results of this computation are unlikely to be all needed at the same time. This causes too many variables to be live at the same time, more than there are available registers, which means that most of them have to be spilled. On the other hand, if those computations were done right before their result is needed, we would reduce its lifespan and thus avoid spilling. Our scheduling algorithm identifies precisely those variables with structurally short lifespans, exploiting the structure of the input Usuba program. For instance, on the naive DES code, the inputs of the S-boxes are computed all at once, but are only used 6 by 6. Therefore, our algorithm schedules those instructions right before they are used, thus removing the need to spill their results.

This algorithm improves performance, as shown in Table 1c: using Usubac's scheduler instead of relying solely on that of the C compiler increases the performance by 10 to 30% on DES. The C compilers struggle to keep the spilling low: from half to two thirds of the assembly instructions are `mov`es. Using Usubac algorithm reduces the number of `mov`es generated by the C compilers by 19% (Clang) to 43% (GCC).

Explicit spilling Conversely, some variables have an inherently long lifespan and will inevitably be spilled. To help the C compiler perform register allocation, we explicitely spill such variables by storing them in arrays. On DES, those variables are typically the outputs of each round, which are potentially not used until the call to the 8^{th} *S-box* of the next round. This reduces the register pressure, and allows the C compiler to find a better register allocation (with less spilling) for the variables exhibiting a shorter lifespan.

Table 1d shows the performance impact of explicitly spilling variables on DES. This optimization heavily depends on the C scheduler and register allocator, which leads to a speedup



(a) DES without transposition

(b) Standard DES with transposition

Figure 3. DES throughput on Intel's Skylake i9-7900X

varying from 0 to 20% depending on the compiler. The assembly code for DES generated by `Clang` (resp. `ICC`) contains 1222 (resp. 1413) fewer `move` instructions when explicitly spilling some variables, which is directly reflected by the speedup.

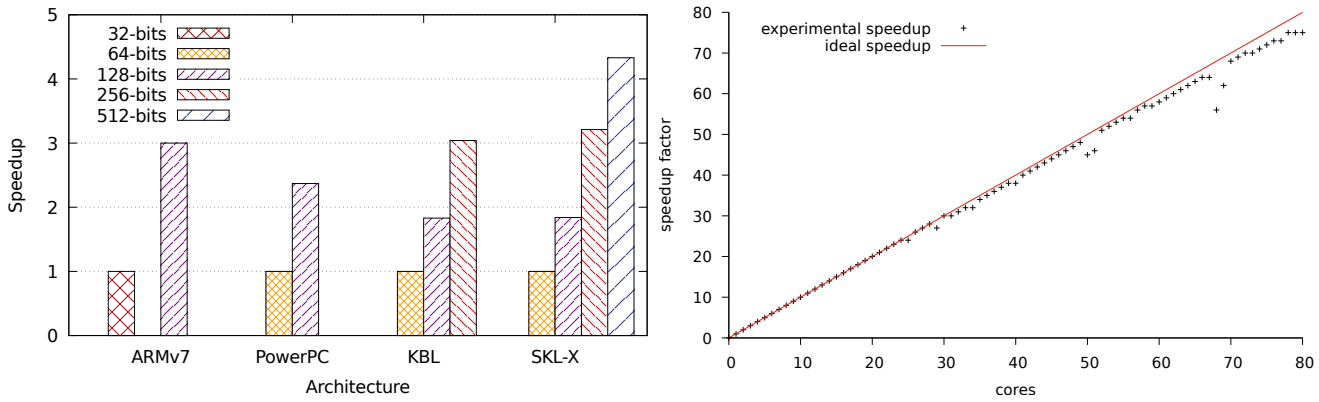
5 Evaluation

We evaluate our compiler using our implementation of DES presented in Section 2. While DES is outdated and should not be used for cryptographic purposes, it provides an interesting experimental platform. First, it was not designed with bitslicing in mind, which puts the expressivity of Usuba to the test: our implementation of DES is an almost literal translation of the DES specification, unencumbered by bitslicing details. Second, there exist several, publicly-available implementations of DES, both in standard and bitsliced form for 64 bit architectures. We chose Kwan's implementation because it is well-known and written in C, enabling us to compare our results across compilers.

5.1 Bitsliced DES without transposition

To isolate the cost of encrypting data from the cost of converting data to a bitsliced format, we first evaluate our implementation of DES *without* performing transposition of the data. Figure 3a shows the throughput of such an implementation (compiled with `ICC` 17.0.2 and running an Intel Skylake i9-7900X), depending on the type of registers used, general purpose 64-bit registers (GP-64), or SIMD registers: SSE on 128 bits, AVX on 256 bits, and AVX-512 on 512 bits. We report the throughput of Kwan's implementation of DES with the label "manual". For a fair comparison, our implementation uses the same *S-boxes* as Kwan (whereas smaller versions have been discovered since [20]): we are therefore comparing algorithmically equivalent programs.

The scaling of our code on vector extensions is slightly sublinear. While the C codes of the scalar and vector programs are very close, there are significant differences between the assembly codes: the scalar code is composed of about 12900 instructions and has an arithmetic intensity of 1.85, while the vector codes are composed of about 10400 instructions and have an arithmetic intensity around 4. The main difference between the two codes is the number of `move` instructions, which directly come from the amount of spilling. This is due to the fact that the vector codes use three-operand instructions while the scalar code only uses destructive two-operand instructions. One might then expect the vector codes to run faster than the scalar code, but this is not the case because Skylake CPUs have 4 scalar ALU ports, and only 3 vector ALU ports. Furthermore, most memory operations can be performed at the same time as some arithmetic operations because they use 3 different ports (2 for loads and 1 for stores). It is worth pointing out that the vector codes are computation bound since their arithmetic intensity is 4, and the vast majority of their memory access are spill-related, and therefore in the L1 cache. Hence, the memory is not the cause of the sublinear scaling on vector extensions. Intel® VTune™ Amplifier reveals that the front-end, and in particular the Micro Instruction Translation Unit (MITE), is limiting the scaling on SSE and even more on AVX. The instruction fetcher can only retrieve 16 bytes of instructions each cycle, which correspond to 4 instructions in the scalar code (whose sizes are around 3.7 bytes) but around 2 or 3 vector instructions, whose sizes are around 4.7 bytes. This is why the vector programs are executed at about 2.6 instructions per cycle (IPC), while the theoretical maximum is above 3.5. The MITE is not an issue in standard vector codes, whose hotsopts are small loops (unlike our code, which is fully unrolled), and therefore benefit from the loopback buffer, which can issue up to 4 micro-operations per cycle.



(a) Speedup per wordsize

(b) Speedup per core

Figure 4. Scaling of Usuba's DES

5.2 Transposition

As mentioned in Section 1, in bitslicing, a word of size m must be transposed to occupy 1 bit in m registers, rather than m bits in 1 register, and more generally, n words of size m become m registers of size n. We used a standard algorithm to do so [12, 22]. We adapted it to the SIMD extensions we are targetting, which do not support shifts of arbitrary length, but offer special permutation instructions (*e.g.* `blend`, `vec_perm`) that can be used instead of masks and shifts. The complexity of the algorithm is $O(n\ log(n))$ for an $n \times n$ matrix. Figure 5 shows the number of cycles needed to transpose 1 bit of input, depending on the register type. The throughput on an Intel Skylake i9-7900X (using code produced by `ICC` 17.0.2) follows the expected sublinear asymptotic complexity. Similar speedup are obtained with ARM's Neon and PowerPC's Altivec extensions.

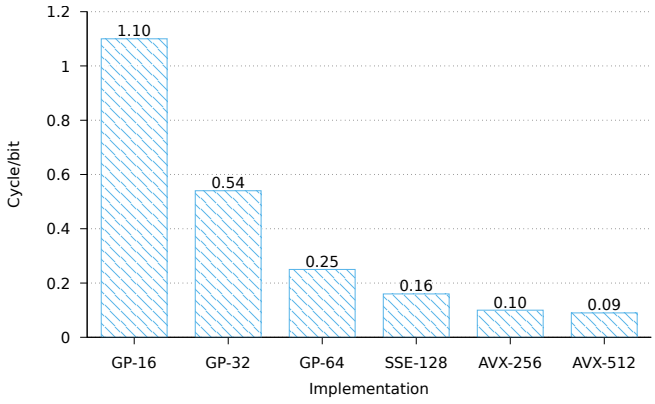


Figure 5. Transposition cost

5.3 Bitsliced DES with transposition

Figure 3b compares the performance of our DES implementations with transposition at various register sizes. For comparison, we also reported the performance of a standard non-bitsliced implementation of DES (from the Crypto++ library [10]). The latter uses general purpose registers of 32 bits mainly, but cannot have its performances increased by using wider registers, unlike the bitsliced versions. Our bitsliced implementation on AVX-512 has a throughput about 15 times higher than a standard DES. The scaling of our implementations is sublinear: $\times$ 1.81 from general purpose 64-bit registers to SSE, and $\times$ 1.75 from SSE to AVX. This is mainly due to the transposition having sublinear complexity.

Figure 4a shows the speedup obtained by using vector extensions on several architecture: SKL-x is the Intel Skylake i9-7900X aforementioned, KBL is an Intel Kaby Lake i7-7500U, PowerPC is a PPC 970MP, and ARMv7 an ARMv7 Raspberry Pi3. The speedup obtained on KBL and SKL-x are very similar. Using PowerPC's 128-bit Altivec extensions offers a speedup of 2.36 over the 64-bit general purpose registers, and using ARM's 128-bit Neon extensions increases performance by a factor 3 compared to the 32-bit registers. Note that the performances for each architecture have been normalized in order to allow a fair comparison of the speedups.

5.4 OpenMP

Another way to increase throughput is to use several cores, which gives (virtually) access to more registers. Usuba can generate code exploiting several cores using OpenMP [9]. We tested the OpenMP code generated by Usuba on a 4x20 cores Intel Xeon E7-8870 v4 (Figure 4b), reporting the speedup relatively to the monocore, non-OpenMP version. The overhead of OpenMP is negligible while the throughput of DES is almost proportional to the number of cores used.

6 Related Work

Bitslicing existing algorithms. Bitslicing was first used in cryptography by Biham [7] on DES. Käsper and Schwabe [15] gave a bitsliced implementation of AES, which runs at 7.59 cycles/byte. Their code, unlike most previous bitsliced code, uses only a few variables: their AES state is in only 8 SSE registers, which allows them to use SSE2-specific permutation instructions. Recent work on bitslicing, such as the bitsliced implementations of Prince, LED and Rectangle by Bao et al. [4], have used similar techniques, by representing the cipher's state on only a few registers instead of dozens or hundreds.

Bitslicing compilers. The only bitslicing compiler we know of, `bsc`, was developed by Pornin [22]. `bsc` inspired the development of our compiler: we borrowed its presentation of permutation tables and lookup tables. Being a proof-of-concept, the language provided by `bsc` is less rich than that of Usuba, and the code generated from it is not optimized for speed nor size, whereas our goal is to be more efficient than hand-written code.

SIMD libraries. A flurry of C++ libraries provide a unified programming model for various SIMD architectures, such as Boot.SIMD [11], MIPP [8], UME::SIMD [14], Sierra [18] or VC [16]. These works are complementary to ours: our intent is to provide a language that (always) compiles to efficient bitsliced code while being amenable to formal verification. To this end, we have implemented specialized SIMD backends and could certainly benefit from piggy-backing on those libraries, much as we currently use OpenMP for multicore processing.

7 Conclusion & Future Work

Usuba is a synchronous dataflow programming language we have designed to write bitsliced programs. It contains specifics constructs to address the specificities of cryptographic algorithms, in particular permutation and lookup tables (Section 2). We presented the compilation steps to get from an Usuba program to an efficient C program (Section 3). The optimizer exploits the dataflow properties of Usuba to make optimizations that most C compiler do not or cannot do as efficiently. We have focused our evaluation on DES but we have also implemented other ciphers such as AES [1], Camellia [3] and Serpent [2].

In future work, we intend to broaden the range of our evaluation to these cryptosystems as well as consolidate our scheduling algorithm across the range of supported architectures.

Acknowledgments

The original idea of a bitslicing compiler was suggested by Xavier Leroy. We are thankful to Intel France and Francois Hannebicq for allowing us to run our experiments on one of their Xeon Skylake Platinium 8168. This work was partially funded by the Émergence(s) program of Paris and the EDITE doctoral school.

References

[1] Specification for the advanced encryption standard (aes). Federal Information Processin Standards Publication 197, 2001.

[2] R. Anderson, E. Biham, and L. Knudsen. Serpent: A proposal for the advanced encryption standard. In *AES*, 1998. doi:10.1.1.86.2107.

[3] K. Aoki, T. Ichikawa, M. Kanda, M. Matsui, S. Moriai, J. Nakajima, and T. Tokita. Camellia: A 128-bit block cipher suitable for multiple platforms - design and analysis. In *SAC*, 2000. doi:10.1007/3-540-44983-3_4.

[4] Z. Bao, P. Luo, and D. Lin. Bitsliced implementations of the PRINCE, LED and RECTANGLE block ciphers on AVR 8-bit microcontrollers. In *ICICS*, 2015. doi:10.1007/978-3-319-29814-6_3.

[5] D. J. Bernstein. Cache-timing attacks on AES. Technical report, 2005. URL https://cr.yp.to/antiforgery/cachetiming-20050414.pdf.

[6] D. Biernacki, J.-L. Colaço, G. Hamon, and M. Pouzet. Clock-directed modular code generation for synchronous data-flow languages. *LCTES*, 2008. doi:10.1145/1379023.1375674.

[7] E. Biham. A fast new DES implementation in software. In *FSE*, 1997. doi:10.1007/BFb0052352.

[8] A. Cassagne, B. L. Gal, C. Leroux, O. Aumage, and D. Barthou. An efficient, portable and generic library for successive cancellation decoding of polar codes. In *LCPC*, 2015. doi:10.1007/978-3-319-29778-1_19.

[9] L. Dagum and R. Menon. OpenMP: An Industry-Standard API for Shared-Memory Programming. *IEEE Comput. Sci. Eng.*, 1998. doi:10.1109/99.660313.

[10] W. Dai. Crypto++ library 5.6. 0, 2009.

[11] P. Estérie, J. Falcou, M. Gaunard, and J. Lapresté. Boost.simd: generic programming for portable simdization. In *WPMVP*, 2014. doi:10.1145/2568058.2568063.

[12] G. Gaubatz and B. Sunar. Leveraging the multiprocessing capabilities of modern network processors for cryptographic acceleration. In *NCA*, 2005. doi:10.1109/NCA.2005.28.

[13] N. Halbwachs, P. Caspi, P. Raymond, and D. Pilaud. The synchronous dataflow programming language Lustre. *Proceedings of the IEEE*, 1991. doi:10.1109/5.97300.

[14] P. Karpinski and J. McDonald. A high-performance portable abstract interface for explicit SIMD vectorization. In *PMAM@PPoPP*, 2017. doi:10.1145/3026937.3026939.

[15] E. Käsper and P. Schwabe. Faster and timing-attack resistant AES-GCM. *CHES*, 2009. doi:10.1007/978-3-540-74735-2_9.

[16] M. Kretz. *Extending C++ for explicit data-parallel programming via SIMD vector types*. PhD thesis, Goethe University Frankfurt am Main, 2015.

[17] M. Kwan. Bitslice DES, 1998. URL http://www.darkside.com.au/bitslice/.

[18] R. Leißa, I. Haffner, and S. Hack. Sierra: a SIMD extension for C++. In *WPMVP*, 2014. doi:10.1145/2568058.2568062.

[19] A. Menezes, P. C. van Oorschot, and S. A. Vanstone. *Handbook of Applied Cryptography*. CRC Press, 1996. ISBN 0-8493-8523-7.

[20] A. Peslyak and R. Rusakov. John the Ripper 1.7.8: DES speedup, 2011. URL http://www.openwall.com/lists/john-users/2011/06/22/1.

[21] A. Pnueli, M. Siegel, and E. Singerman. Translation validation. In *TACAS*, 1998. doi:10.1007/BFb0054170.

[22] T. Pornin. *Implantation et optimisation des primitives cryptographiques*. PhD thesis, Laboratoire d'Informatique de l'École Normale Supérieure, 2001.