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# Usuba

## Optimizing & Trustworthy Bitslicing Compiler

Darius Mercadier

Pierre-Évariste Dagand

Lionel Lacassagne

Gilles Muller

firstname.name@lip6.fr

Sorbonne Universités—UPMC Univ Paris 06

CNRS—Inria—LIP6 UMR 7606

### Abstract

Bitslicing is a programming technique commonly used in cryptography that consists in (efficiently) implementing a combinatorial 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 multiple 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];
}
```

For example, on input  $0110_b = 6_d$ , this function returns the seventh (note the 0-indexing) element of the table, which is  $10_d = 1010_b$ .

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 capacities of the CPU are 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  $\text{bool}^4 \rightarrow \text{bool}^4$ : given an input of 4 Booleans, it computes 4 Booleans corresponding to the output of the *S-box*. For instance, feeding this circuit with  $(\text{false}, \text{true}, \text{true}, \text{false}) = 0110_b = 6_d$ , will produce the outputs  $(\text{true}, \text{false}, \text{true}, \text{false}) = 1010_b = 10_d$ , as before. Here, only variables of Boolean type are used, but the same program could manipulate `uint64_t` values. Conceptually, this would amount to execute 64 such circuits in parallel: one circuit applying to the bits of rank 0 of the registers, another one for 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

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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], &18, &116, &122, &130);
s2 (r3^k[27], r4^k[6], r5^k[54], r6^k[48],
    r7^k[39], r8^k[19], &112, &127, &11, &117);
s3 (r7^k[53], r8^k[25], r9^k[33], r10^k[34],
    r11^k[17], r12^k[5], &123, &115, &129, &15);
```

The full implementation takes 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 and does not exploit vector extensions offering registers of 128 bits and more on modern machines.

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 synchronous 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 3.3). 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 4). 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.

USUBA is also trustworthy: we apply translation validation [22] 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. [21]) 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* or *lookup tables*. A node can be understood as a component in a circuit diagram: it is a standalone object with specified inputs and outputs.

A node (Fig. 1,  $\langle nd \rangle$ ) specifies its input, output and lexical typed variables as well as a list of equations  $\langle eqs \rangle$ . Types  $\langle typ \rangle$  can be Booleans or arrays of size  $n$  (for a fixed  $n \in \mathbb{N}^*$ , known at compile-time). For convenience, we also offer a type  $un$ , which (concisely) stands for `bool[n]`. An equation  $\langle eq \rangle$  is either a single assignment or a quantified (but statically bounded) definition of a group of equations. A formal variable  $\langle var \rangle$  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  $\langle expr \rangle$  are either variables, unsigned integer constants, tuples, unary or binary bitwise operations or node calls. Unary and binary operators ( $\langle unop \rangle$  and  $\langle binop \rangle$ ) correspond exactly to the corresponding C operators. Arithmetic expressions  $\langle aexpr \rangle$  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

```

⟨nd⟩ ::= node f(⟨tv⟩+) returns (⟨tv⟩+)
      vars ⟨tv⟩+ let ⟨eqs⟩ tel
⟨tv⟩ ::= x : ⟨typ⟩
⟨typ⟩ ::= bool | ⟨typ⟩[n]
⟨eqs⟩ ::= ⟨eq⟩ | ⟨eqs⟩;⟨eqs⟩
⟨eq⟩ ::= ⟨lhs⟩ = ⟨expr⟩
      | forall i in [⟨aexpr⟩, ⟨aexpr⟩], ⟨eqs⟩
⟨lhs⟩ ::= ⟨var⟩ | (⟨var⟩ ⟨var⟩+)
⟨var⟩ ::= x | x[⟨aexpr⟩+]
      | x[⟨aexpr⟩...⟨aexpr⟩]
⟨expr⟩ ::= x | n | (⟨expr⟩⟨expr⟩+)
      | ⟨unop⟩⟨expr⟩ | ⟨expr⟩⟨binop⟩⟨expr⟩
      | f(⟨expr⟩+)
⟨unop⟩ ::= ~ | ⟨binop⟩ ::= & | | | ^
⟨aexpr⟩ ::= i | n | ⟨aexpr⟩⟨abinop⟩⟨aexpr⟩
⟨abinop⟩ ::= + | - | / | %

```

Figure 1. Usuba grammar

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.

**Permutation** 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 table** USUBA also supports the declaration of lookup tables in order to specify *S-boxes*. These declarations are then converted to circuits by either looking up a database of known circuits or, failing to find one, compiling it using binary decision diagrams (BDDs).

The first S-box of DES is thus specified by:

```

table sbbox_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.

## 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 in the setting of a synchronous dataflow language. 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:

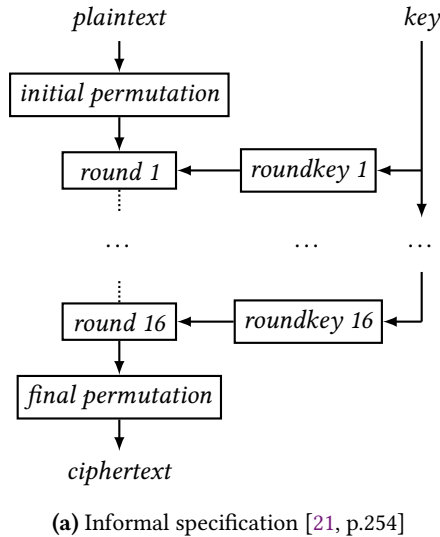
$$\begin{array}{ll}
 x1 = \sim a.4; & x4 = x3 \wedge x2; \\
 x2 = \sim a.1; & x2 = \sim a.1; \\
 x3 = a.4 \wedge a.3; & \cong x1 = \sim a.4; \\
 x4 = x3 \wedge x2; & x3 = a.4 \wedge a.3;
 \end{array}$$

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 be replaced by that variable. The compiler backend eventually produces a valid scheduling, which consist 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



```

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

optimizations are then applied on the program (Section 3.3), 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 3.3) 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.

### 3.3 Back-end

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 are no control structures, which means that the code is in single static assignment (SSA) form with no  $\varphi$  node. Moreover, information from the original USUBA program are available, and can be used to optimize the scheduling of arrays after their expansion.

This section presents the optimizations done by USUBA, and their impact on the performance of the DES code generated from the USUBA 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. We ran the codes 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*.

| 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

| 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

|     | 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   | 1.26    | 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

**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 generates slightly smaller C files, and guarantees that it will be done, no matter 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 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 Usabac 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. C compilers tend to avoid increasing code size too much, thus inlining very few of the definitions generated by USUBA. On the contrary, USUBA aggressively inlines every function exploiting the fact that side-stepping the call-stack improves performance considerably. 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 Usabac (3), Clang chooses to only inline the S-boxes (2), thus gaining 10% performance, but fails to inline the round function. However, Usabac 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 in the assembly code. 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, coming from the unfolding of tuples. For example, the USUBA operation  $x = a \& b$ , where  $x$ ,  $a$  and  $b$  are two *un*, normalizes to  $n$  AND instructions, but the  $n$  results of this computation will likely not be used all 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 results are needed, it would reduce the lifespan of those variables, which would reduce their 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 Usabac’s scheduler instead of relying solely on

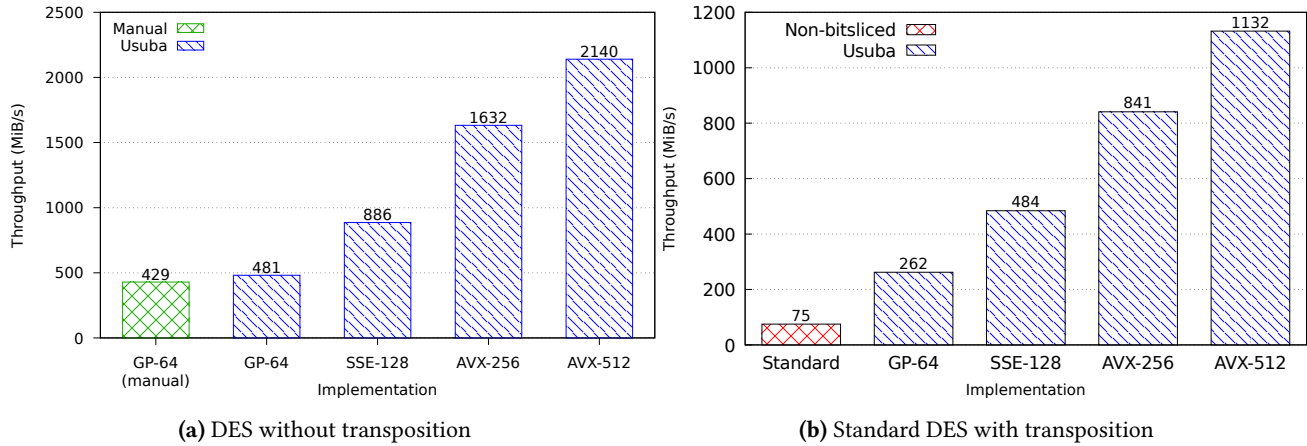


Figure 3. DES throughput on Intel’s Skylake i9-7900X

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 instructions of the code are moves. Using Usubac algorithm reduces the number of moves generated by the C compilers by 19% (Clang) to 43% (GCC).

**Explicit spilling** The aforementioned optimizations are not sufficient to beat hand-written code. The code contains many more variables than there are available registers, which introduces a lot of spilling. While some variables have a long lifespan and therefore obviously need to be spilled, some are more localized and thus should not be spilled. To help the C compiler perform register allocation, we explicitly spill variables with a long lifespan by storing them in arrays. This reduces the register pressure, and allows the C compiler to find a better register allocation (with less spilling) for variables with a short 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 varying from 0 to 20%. 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 performance.

## 4 Evaluation

We evaluated the performance of the DES code generated from the USUBA implementation 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.

### 4.1 Bitsliced DES without transposition

We can omit the conversion of the data to a bitslice format and compute DES: the inputs are loaded as is in the registers, without performing any transposition. This does not compute a standard DES, but can still be used if both the encrypter and decrypter use bitslicing. 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 use the S-boxes computed by Kwan [18], as they are incorporated in the compiler’s database. We report the throughput of Kwan’s implementation of DES with the label “manual”.

Doubling the size of the registers from 64 to 128 bits doubles the performance, as twice as many data can be encrypted at once. However, there is only speedup of 1.73 from the 128-bit SSE to the 256-bit AVX. We conjecture that this is because the CPU can optimize SSE instructions by pairing them and using AVX instructions instead. For instance, two and operations on 128 bits can be combined into a single and operation on 256 bits. The manual implementation is 15% slower than our implementation on 64-bit registers, as mentioned in Section 3.3. Using AVX-512 does not offer twice the speed of AVX registers, but still allows us to obtain a throughput of more than 2 GiB/s.

### 4.2 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

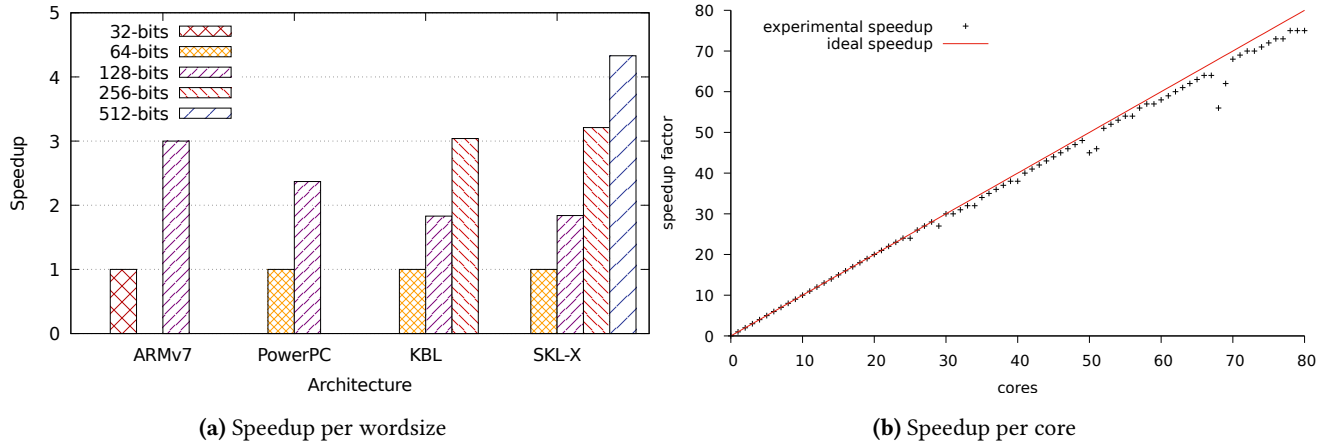


Figure 4. Scaling of USUBA’s DES

do so, whose pseudo-code can be found in Gaubatz and Sunar [12], and a detailed explanations in Pornin [23]. We adapted it to the SIMD extensions we are targetting, which do not allow inter-lane bit-shifts. The complexity of the algorithm is  $O(n \log(n))$  for an  $n \times n$  matrix. Figure 5 shows the cycles needed to transpose 1 bit of input, depending on the register used. 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.

4.3 Bitsliced DES with transposition

Figure 3b compares the performance of our DES implementations with transposition on different 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 bit-sliced implementation on AVX-512 has a throughput about

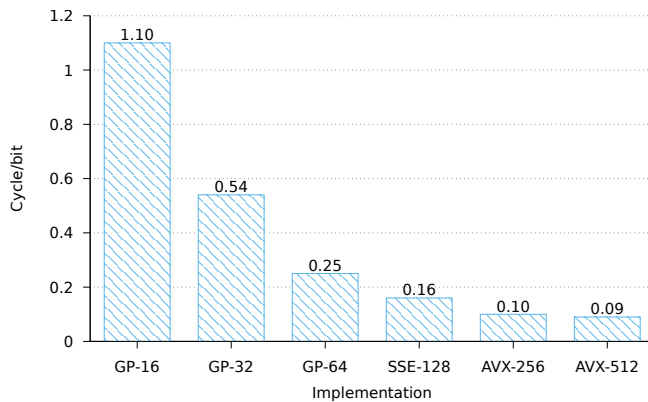


Figure 5. Transposition cost

15 times higher than a standard DES.

The scaling of our implementations is slightly sublinear:  $\times 1.81$  from general purpose 64-bit registers to SSE, and  $\times 1.75$  from SSE to AVX. This is 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.

4.4 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). The throughput of DES is almost proportional to the number of cores used. Overall, using 78 cores or more yields a speedup of  $\times 75$ . Using more than 78 cores (out of the 80 available) does not increase the throughput, as other tasks running on the machine – including the OS – are eventually scheduled on the same cores as our DES.

5 Related Work

**Bitslicing existing algorithms.** Bitslicing was first used in cryptography by Biham [7] on DES. The best known software AES is from Käsper and Schwabe [15], that 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. Due to their parallel nature, GPUs have been used to improve the performance of bitslicing algorithm [20, 24], yielding far better throughput than on any CPU.

**Bitslicing compilers.** The only bitslicing compiler we know of, *bsc*, was developed by Pornin [23]. *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* [19] 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.

## 6 Conclusion & Future Work

*USUBA* is a synchronous dataflow programming language we have designed to write bitsliced programs. In particular, it contains specific 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. Also, GPUs would offer improved performance over CPU due to their parallel nature, which can be efficiently exploited with bitslicing.

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