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Trustworthy Bitslicing Compiler
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Usuba
Optimizing & Trustworthy Bitslicing Compiler

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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:

```c
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 \( \mathbf{0}110_b = 6_{10} \), this function returns the seventh (note the 0-indexing) element of the table, which is \( 100_{10} = 4_{10} \).

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:

```cpp

node sbox (a,b,c,d:boolean) return (w,x,y,z:boolean)
vars t01,t02,t03,t04,t05,t06,t07,
t08,t09,t10,t11,t12,t13,t14: boolean
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;
```

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 bool^n \rightarrow 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 \((0, 1, 1, 0) = 0110_b = 6_{10}\), will produce the outputs \((1, 0, 1, 0) = 1010_b = 10_{10}\), 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 trans-
position transforming $n \times m$-bit inputs into $m \times n$-bit registers.

Bit slicing is thus able to increase performance by exploit-
ing data-parallelism, while improving security by disabling
(cache-timing attacks. Historically, bit slicing is a manual
process. For instance, here is a snippet of a bit sliced imple-
mentation of the Data Encryption Standard (DES) by Kwan [17]:

$$s1 \ (r31^k[47], \ r0^k[11], \ r1^k[26], \ r2^k[3], \ r3^k[13], \ r4^k[41], \ \&18, \ \&16, \ \&12, \ \&30);$$
$$s2 \ (r3^k[27], \ r4^k[6], \ r5^k[54], \ r6^k[48], \ r7^k[39], \ r8^k[19], \ \&12, \ \&27, \ \&11, \ \&17);$$
$$s3 \ (r7^k[53], \ r8^k[25], \ r9^k[33], \ r10^k[34], \ r11^k[17], \ r12^k[5], \ \&23, \ \&15, \ \&129, \ \&15);$$

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 bit sliced algorithm is fundamentally a cir-
cuit written in software, we designed USUBA, a synchronou-
dataflow programming language for implementing circuits
in software. This paper makes the following contributions:

- We have designed USUBA, a synchronous dataflow lan-
guage 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, per-
mutations, binary tuples, arrays).

- We have implemented a compiler, USUBA
  to C (Section 3). It applies standard dataflow compila-
tion techniques [6] as well as domain-specific trans-
formations, such as handling bitvectors, expanding
permuations and lookup tables.

- We have implemented several optimizations (Section
4). This includes standard transformations such as
inlining, constant folding, common subexpression eli-
mination (CSE) and copy propagation, as well as a doma-
inspecific instruction scheduling algorithm. The latter
is tailored to handle the unusual structure of our pro-
grams (large number of live variables, absence of con-
trol 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 (Sec-
tion 5). At equivalent word size, our USUBA implemen-
tation is 15% faster than a functionally-equivalent,
hand-tuned implementation of DES [17]. Besides, the
same USUBA program can also be compiled to manip-
ulate larger wordsizes (such as those offered by the
AVX-512 extensions), yielding a 350% improvement
over the hand-tuned, fixed wordsize implementation.

Figure 1. USUBA grammar

USUBA is also trustworthy: we apply translation valida-
tion [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 pro-
vided by the user). We shall not dwell on these techniques
in the present paper, the description of the formal seman-
tics and the evaluation of the verification framework being
beyond the scope of the workshop.

2 USUBA

USUBA is a synchronous datalflow language akin to a hard-
ware description language (HDL). It enables the concise and
high-level description of software circuits that are then com-
plied into a bitsliced implementation. The benefits of USUBA
are twofold. First and by design, any software circuit spe-
cified in USUBA admits a bitsliced (and therefore efficient)
implementation. Second, the informal description of symmet-
ic 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,
permuations 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

\[
\begin{align*}
\langle nd \rangle &::= node \ f(\langle tv \rangle^+) \ \text{return} \ (\langle tv \rangle^+) \\
\langle tv \rangle &::= x : (\text{typ}) \\
\langle typ \rangle &::= \text{bool} \ | \ (\text{typ})[n] \\
\langle eqs \rangle &::= \langle eq \rangle \ | \ (\text{eqs}) \ (\text{eqs}) \\
\langle eq \rangle &::= \langle lhs \rangle = (\langle expr \rangle) \\
&\quad | \ \text{forall} \ i \ \text{in} \ [\langle aexpr \rangle, \ (\text{aexpr})], \ (\text{eqs}) \\
\langle lhs \rangle &::= \langle \text{var} \rangle \ | \ (\langle \text{var} \rangle \langle \text{var} \rangle^+) \\
\langle var \rangle &::= x \ | x \langle (\text{aexpr})^+ \rangle \\
&\quad | \ x \langle (\text{aexpr}) \ldots \langle \text{aexpr} \rangle \rangle \\
\langle expr \rangle &::= x \ | \ n \ | \ (\langle expr \rangle \langle expr \rangle^+) \\
&\quad | \ \langle \text{unop} \rangle \langle expr \rangle \ | \ (\langle expr \rangle \langle \text{binop} \rangle \langle expr \rangle \langle expr \rangle) \\
&\quad | \ f(\langle expr \rangle^+) \\
\langle \text{unop} \rangle &::= \& \ | \ | \ | \ | ^ \\
\langle aexpr \rangle &::= i \ | \ n \ | \ \langle \text{aexpr} \rangle \langle \text{abinop} \rangle \langle \text{aexpr} \rangle \\
\langle \text{abinop} \rangle &::= + \ | \ - \ | \ / \ | \ % 
\end{align*}
\]

This 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 bit sliced algorithm is fundamentally a cir-
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nation (CSE) and copy propagation, as well as a doma-
inspecific instruction scheduling algorithm. The latter
is tailored to handle the unusual structure of our pro-
grams (large number of live variables, absence of con-
trol 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 (Sec-
tion 5). At equivalent word size, our USUBA implemen-
tation is 15% faster than a functionally-equivalent,
hand-tuned implementation of DES [17]. Besides, the
same USUBA program can also be compiled to manip-
ulate larger wordsizes (such as those offered by the
AVX-512 extensions), yielding a 350% improvement
over the hand-tuned, fixed wordsize implementation.
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

Figure 2. DES encryption algorithm

offer a type un, 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:

\[
\begin{align*}
x_1 &= \lnot a.4; \quad x_4 = x_3 \land x_2; \\
x_2 &= \lnot a.1; \quad x_2 = \lnot a.1; \\
x_3 &= a.4 \land a.3; \quad x_1 = \lnot a.4; \\
x_4 &= x_3 \land x_2; \quad x_3 = a.4 \land a.3;
\end{align*}
\]

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 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 \( \varphi \) 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
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 $(\text{left}, \text{right}) = \text{des}[16]$ 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 Usuba 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.

### Table 1. Normalized performance impact of the optimization passes

<table>
<thead>
<tr>
<th>Compiler</th>
<th>without</th>
<th>with</th>
<th>speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCC</td>
<td>1.00</td>
<td>1.11</td>
<td>× 1.11</td>
</tr>
<tr>
<td>ICC</td>
<td>1.17</td>
<td>1.35</td>
<td>× 1.15</td>
</tr>
<tr>
<td>Clang</td>
<td>1.36</td>
<td>1.36</td>
<td>× 1.07</td>
</tr>
</tbody>
</table>

(a) CSE-CP

<table>
<thead>
<tr>
<th>Compiler</th>
<th>without</th>
<th>with</th>
<th>speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICC</td>
<td>1.08</td>
<td>1.11</td>
<td>× 1.11</td>
</tr>
<tr>
<td>Clang</td>
<td>1.12</td>
<td>1.11</td>
<td>× 1.11</td>
</tr>
<tr>
<td>GCC</td>
<td>1.00</td>
<td>1.07</td>
<td>× 1.07</td>
</tr>
</tbody>
</table>

(e) Scheduling

### Scheduling

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 aggressively 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 Usuba (3), Clang chooses to only inline the S-boxes (2), thus gaining 10% performance, but fails to inline the round function. However, Usuba 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.

### Table 1b. Normalized performance impact of explicitly spilling

<table>
<thead>
<tr>
<th>Compiler</th>
<th>without</th>
<th>with</th>
<th>speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICC</td>
<td>1.26</td>
<td>1.41</td>
<td>× 1.12</td>
</tr>
<tr>
<td>Clang</td>
<td>1.16</td>
<td>1.40</td>
<td>× 1.21</td>
</tr>
<tr>
<td>GCC</td>
<td>1.00</td>
<td>1.01</td>
<td>× 1.01</td>
</tr>
</tbody>
</table>

(d) Explicit spilling

### Scheduling

Inlining

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### Scheduling

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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 aggressively 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 Usuba (3), Clang chooses to only inline the S-boxes (2), thus gaining 10% performance, but fails to inline the round function. However, Usuba 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.

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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 frontend, 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.
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 targeting, 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.

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 speed-up 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 specific constructs to address the specifics 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.

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