FaCT: A DSL for Timing-Sensitive Computation

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Based on slides from Sunjay Cauligi

Goal: Constant-Time Code

- Constant-time code: timing is independent of secrets
  - Variable-time instruction
  - Memory accesses
  - Conditional branches
  - Early termination

```
if (sec)
    x = a;
} else {
    x = b;
}
```

Motivation: Constant-Time Code is Messy

- Existing techniques include using bitmasks, CMOVs, ORAM, etc.
- The problem:
  - Manually optimized code is messy/unreadable/difficult to reason about correctness
  - Automatically obfuscated code incurs high performance overhead

```
if (sec)
    x = a;
} else {
    x = b;
}
```

```
x = (sec & a) | (~mask & b)
```

```
(sec) CMOV x = a
(!sec) CMOV x = b
```

Rane et. al. Raccoon: closing digital side-channels through obfuscated execution. SEC'15

Threat Model

- Attacker can observe execution time of target programs
- Not concretely stated in the paper
  - Instruction execution “trace” should be independent from secrets
- However, execution time is determined by micro-arch states
  - Thus, miss a computer architecture model, characterized by which kinds of instructions can leak information and which can not, e.g., arithmetic instructions

Overview

- A DSL for writing readable constant-time code

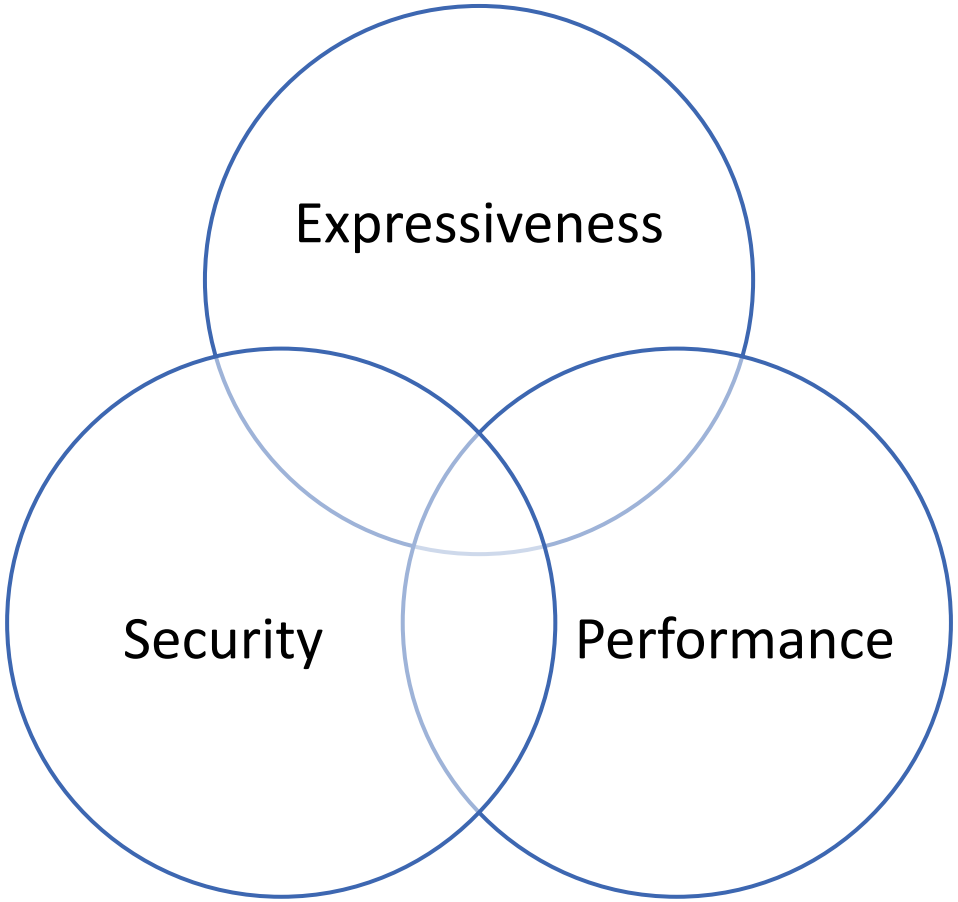
- Transform **secret control flow** to constant-time
  - Transform code that leaks secret via early return, conditional branch
  - Reject programs that leak secret via memory accesses, loop iterations, variable-time instructions

- Ensure transformations can be performed safely

A DSL Trade-offs Among

An example:

To address the imprecision problem of static information flow analysis, remove pointers and disallow recursive typed references



Strengths (Potential Long-term Impacts)

- Provide a great abstraction
  - For SW developers, easy to write constant-time programs
  - For compiler developers, use different techniques to achieve the constant-time goal
    - **ctselect** compiles to a series of bitmasks or the CMOV instruction on x86_64
  - For HW people, performance optimization for execution on public data
- Well-defined typing systems for information flow tracking and formal verification
- A user study to show how easy to write programs using FaCT

A Controversial Contribution

- Reject programs that leak secret via memory accesses, loop iterations, variable-time instructions
  - Put the pressure on programmers. What about AES? Is it really a good trade-off?
  - How much time is spent on manually fixing these problems?

O(1)

```
x = buffer[secret_index];
```

O(n)

```
for (uint32 i = 0 to len buffer) {
    if (i == secret_index) {
        x = buffer[i];
    }
}
```

Limitations/Questions

- Impacts of compiler optimizations of FaCT generated code
  - Security evaluation using *deduct* is not sufficient
  - More information about generated binary sizes may help reason about the performance improvements

- It would be helpful to elaborate more on the trade-offs/reasons for picking the specific design choice in the paper

Reparaz et al. Dude, is my code constant time? DATE'17

FaCT Technique Details

Explicit Secrecy and Information Flow Tracking

- How to handle `st(sec_val, pub_addr)` ?

```
secret uint32 decrypt(
        secret uint32 key,
        public uint32 msg) {

    if (key > 40) {
        ...
    }


    ...

}
```

```
secret uint32 decrypt(
        secret uint32 key,
        public uint32 msg) {

    if (key > 40) {
        ...
    }


    ...

}
```

Type system detects leaks via...

- Conditional branches
- Early termination
- Function side effects

FaCT transforms these

- Memory access patterns
- Direct assignment
- …

FaCT disallows these

Transform Secret Conditionals

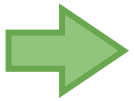
```
if (s) {
    x = 40;
} else {
    x = 19;
    y = x + 2;
}
```

```
x = -s & 40 | (s-1) & x;
```

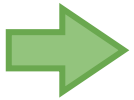
```
x = (s-1) & 19 | -s & x;
y = (s-1) & (x + 2) | -s & y;
```

Transform Secret Returns

```
if (s) {
  return 40;
}
```



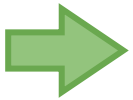
```
if (s) {
  if (!done) {
    rval = 40;
    done = true;
  }
}
```



```
rval = (-s & (done-1)) & 40 | ...
done = (-s & (done-1)) & true | ...
```

Transform Conditional Functions

```
void foo(secret mut uint32 x) {
    x = 5;
}
...
if (sec) {
    foo(x);
}
```



```
void foo(secret mut uint32 x, secret bool
callCtx) {
        x = ctselect(callCtx, 5, x);
}
...
foo(x, sec);
```

Unsafe transformations

```
if (j < secret_len) {
    x = arr[j];
}
```

```
x = -(j < secret_len) & arr[j]
      | ((j < secret_len)-1) & x;
```

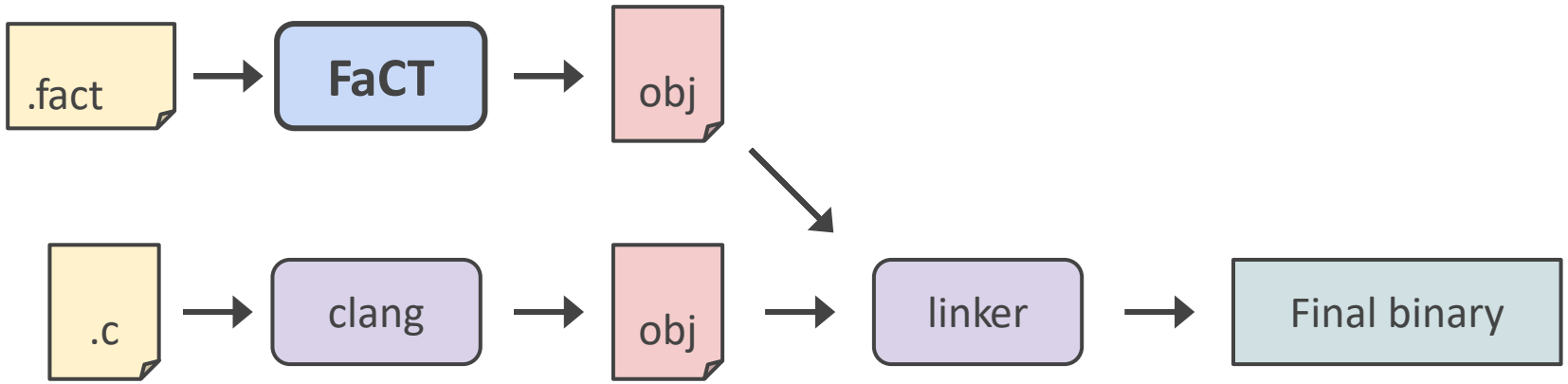
What if j > len arr?

Out of bounds access!

Check for out-of-bounds accesses; Solve constraints using Z3

Porting code to FaCT

- Rewrite the whole library
- Rewrite a function (and callees)
- Rewrite a chunk of code



Real Code Needs Escape Aatches

- **Declassify** secrets to public
  - secretbox:

```
if (!declassify(crypto_verify(...))
  return false;
```

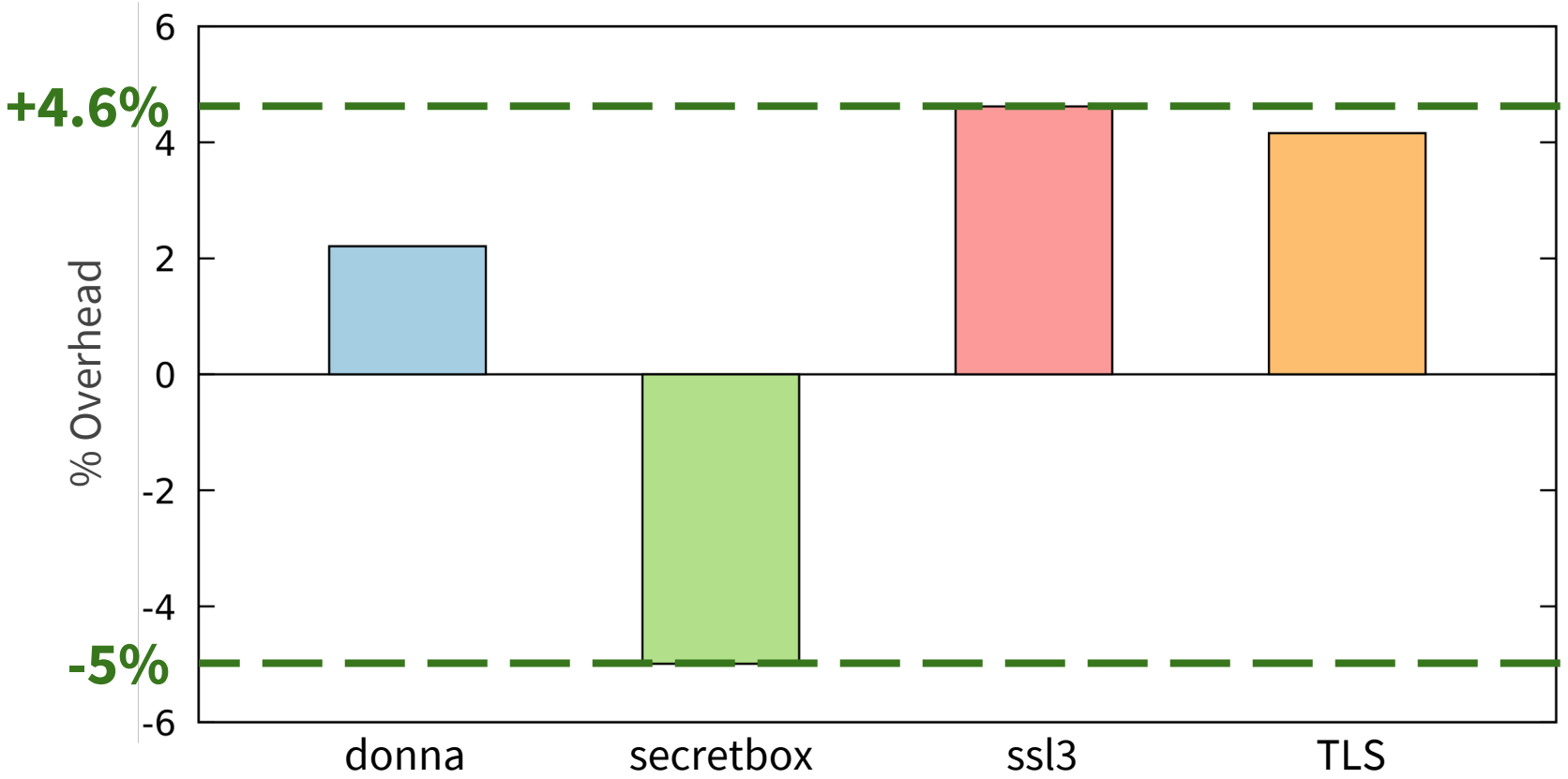
  - TLS:

```
b = pmac[declassify(i)];
```

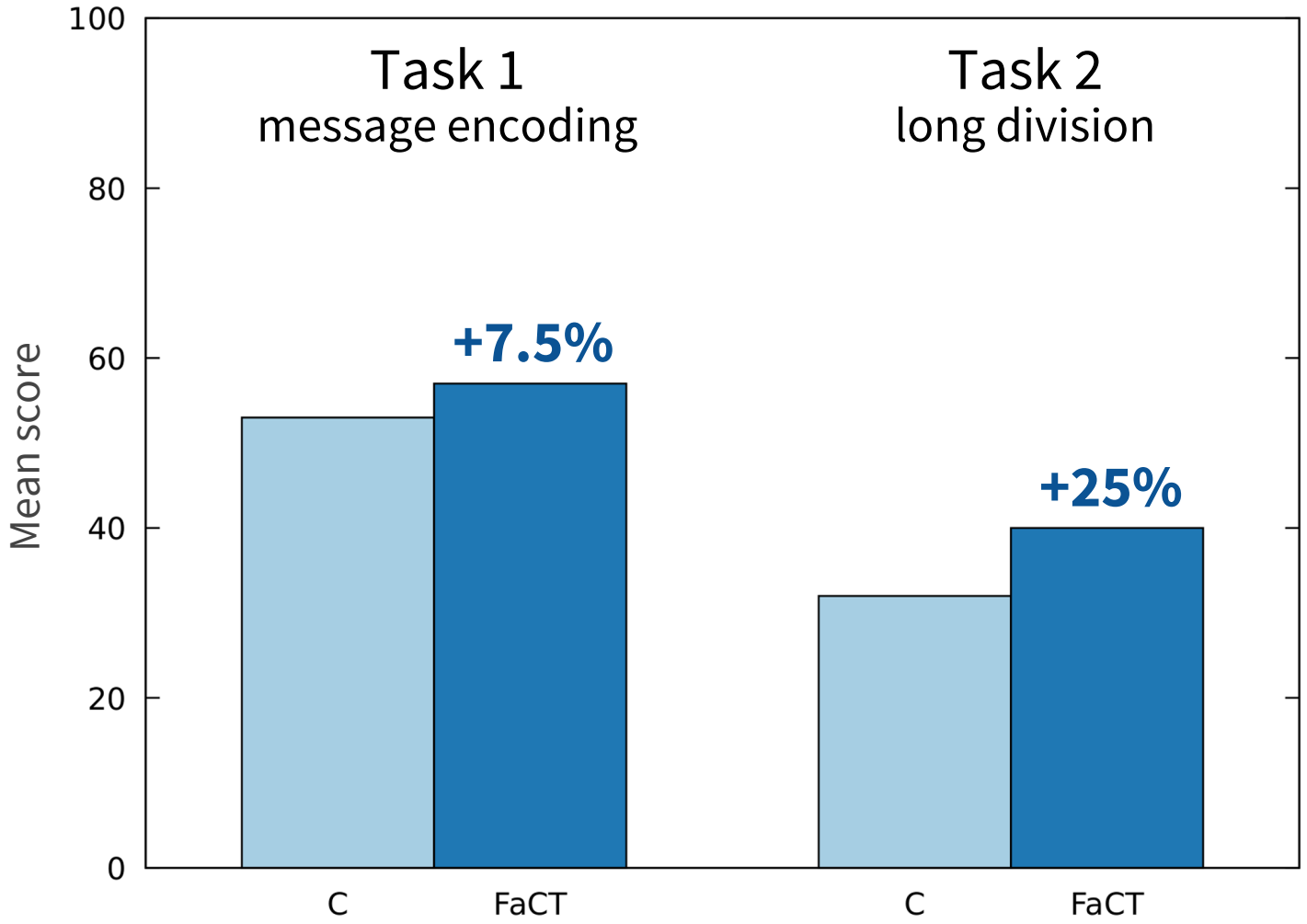
- **Assume** constraints for solver
  - Function preconditions
  - Invariants for mutable variables
- **Extern** function declarations
  - OpenSSL: AES + SHA1 implementations

Performance Evaluation

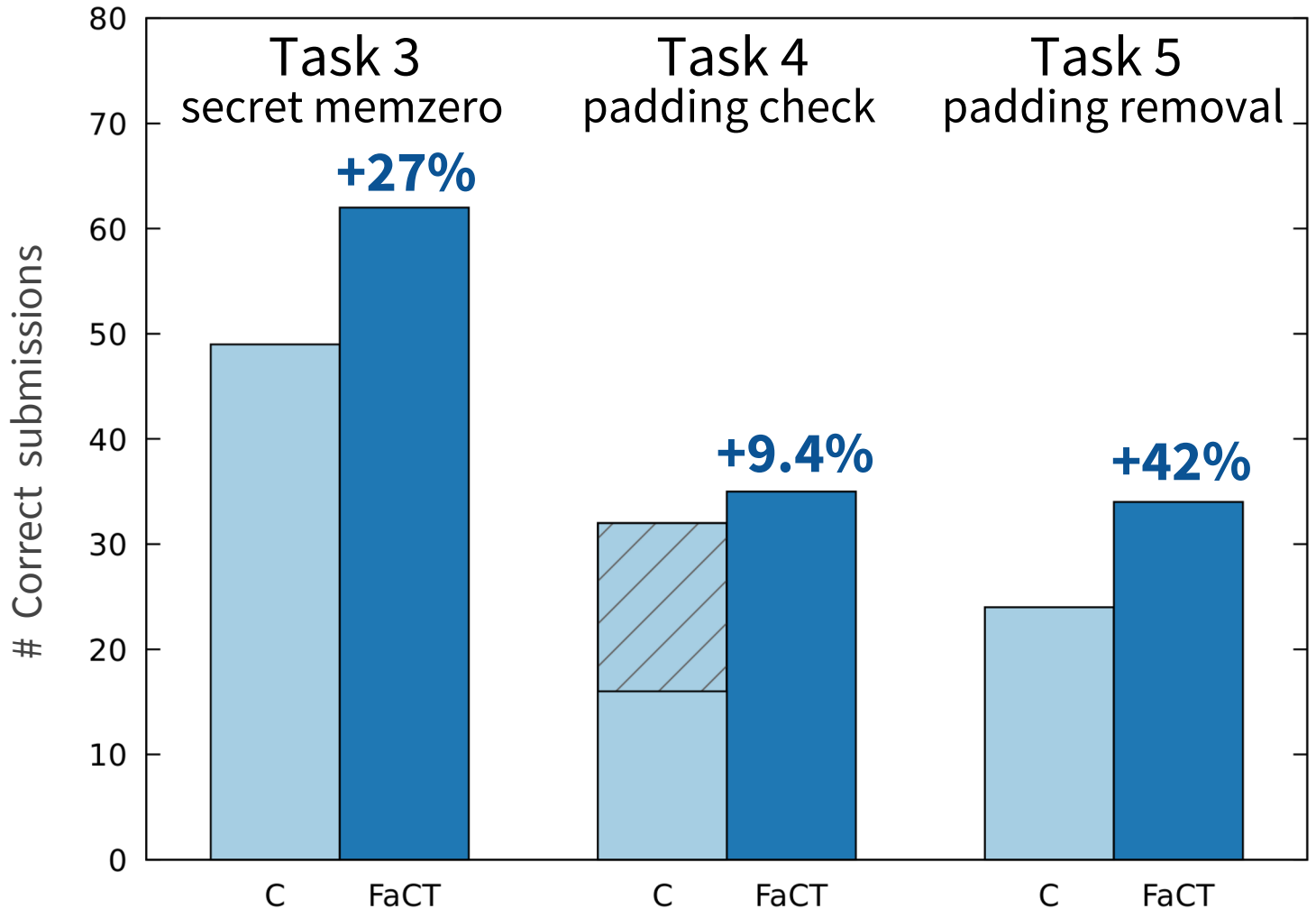
- Optimized with **same optimization flags**
- **Empirically tested** to be constant-time



Understanding constant-time code



Writing constant-time code



Discussion Questions on HW/SW

- Given modern computers have execution units that may not be constant time (specifically division), even a static flow of instructions may not execute with constant total time. What would it take to make sure said execution units operate in a constant time? Division is rare in crypt, so maybe just avoiding it altogether?

- What other processor optimizations exist that will make constant-time operation hard or impossible?

- If a given piece of code is made timing-insensitive, is it possible for power side-channels to still be present?

Discussion Questions on Code Transformation

- Would a lower level solution to the constant time problem be more effective?
- Could we further extend such constant-time reasoning to the optimizer to formally verify the entire compilation flow?
- Is there a more efficient way for the front-end compiler to operate than return statements -> conditionals and then conditionals -> constant time code?

Discussion Questions on Usage

- Are there any cryptographic constructs which are unable to be expressed in FaCT?

- Has there been any further user studies done? If so, what have they shown? If not, what could we expect to see?

- How well do secrets propagate through the type system in practice? For example, if I as an inexperience cryptographer produce a cipher where I mark my salt, my key, and my plaintext as secret, is this sufficient? Is it overkill?