

CBMC-GC: Secure Two-Party Computations in ANSI C



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Data Privacy — The Traditional Approach

Data privacy relies on several technical and administrative approaches:

- Legal requirements
- Policies
- Audits
- Training
- Technical means (access control, network security, intrusion detection)
- Physical security

Does it work?

Restaurant chain customers' credit card data stolen

The Boston Globe

By Bruce Mohl, Globe Staff | October 1, 2007

Not Your Average Joe's, a Massachusetts restaurant chain, said yesterday that thieves have stolen credit card information from its customers.

The Dartmouth-based chain estimated less than 3,500 of the 350,000 customers it served in August and September had their credit card information stolen. The 14-restaurant chain said it is working with the US Secret Service and major credit card companies to determine how the data theft occurred and precisely how many customers were affected.

Today, the chain plans to post on its website a notice to customers about the security breach.

Diana Pisciotta, a spokeswoman for Not Your Average Joe's, said the chain decided to check their credit card statements with companies about any suspicious charges but not responsible for fraudulent activity on them.

"We're doing this out of an abundance of caution and forthright with our customers," she said.

Stolen computer contained info from 88,000 patients at Staten Island hospital

by Staten Island Advance
Wednesday April 30, 2008, 4:37 PM

Computer equipment [stolen from an administrative office in Clifton in December](#) contained personal information from 88,000 patients that have been treated at Staten Island University Hospital.

After four months with no arrests, hospital administrators are just now beginning the process of sending out letters to patients whose names, Social Security and health insurance numbers were contained in computer files on a desktop computer and a backup hard drive stolen Dec. 29 from the hospital's finance office at 1 Edgewater Plaza.

"The hospital is in the process of issuing a statement to the patient involved in which one year of financial records of a hospital statement, released by spokeswoman said.

News Site of the Year | The 2008 Newspaper Awards

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From The Times

January 19, 2008

Personal data of 600,000 on lost laptop



Michael Evans, Defence Editor

A junior Royal Navy officer is facing a court martial after a laptop containing the personal data of 600,000 people, including serving personnel and thousands of people who have shown an interest in a military career, was stolen from his car.

The loss of the laptop was considered to be so serious that Des Browne, the Defence Secretary, will make a statement to the Commons early next week.

TIMES RECOMMENDS

- > MPs back creation of human-animal embryos
- > Bank Holiday plan to celebrate Armed Forces
- > Wanted: criminal law expert to be new DPP

EXCLUSIVE EXTRACTS



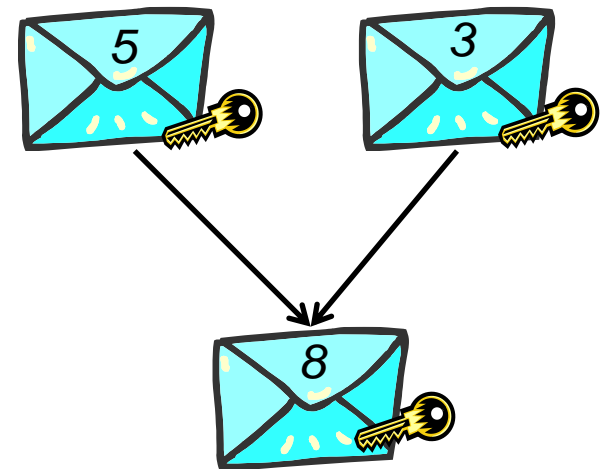
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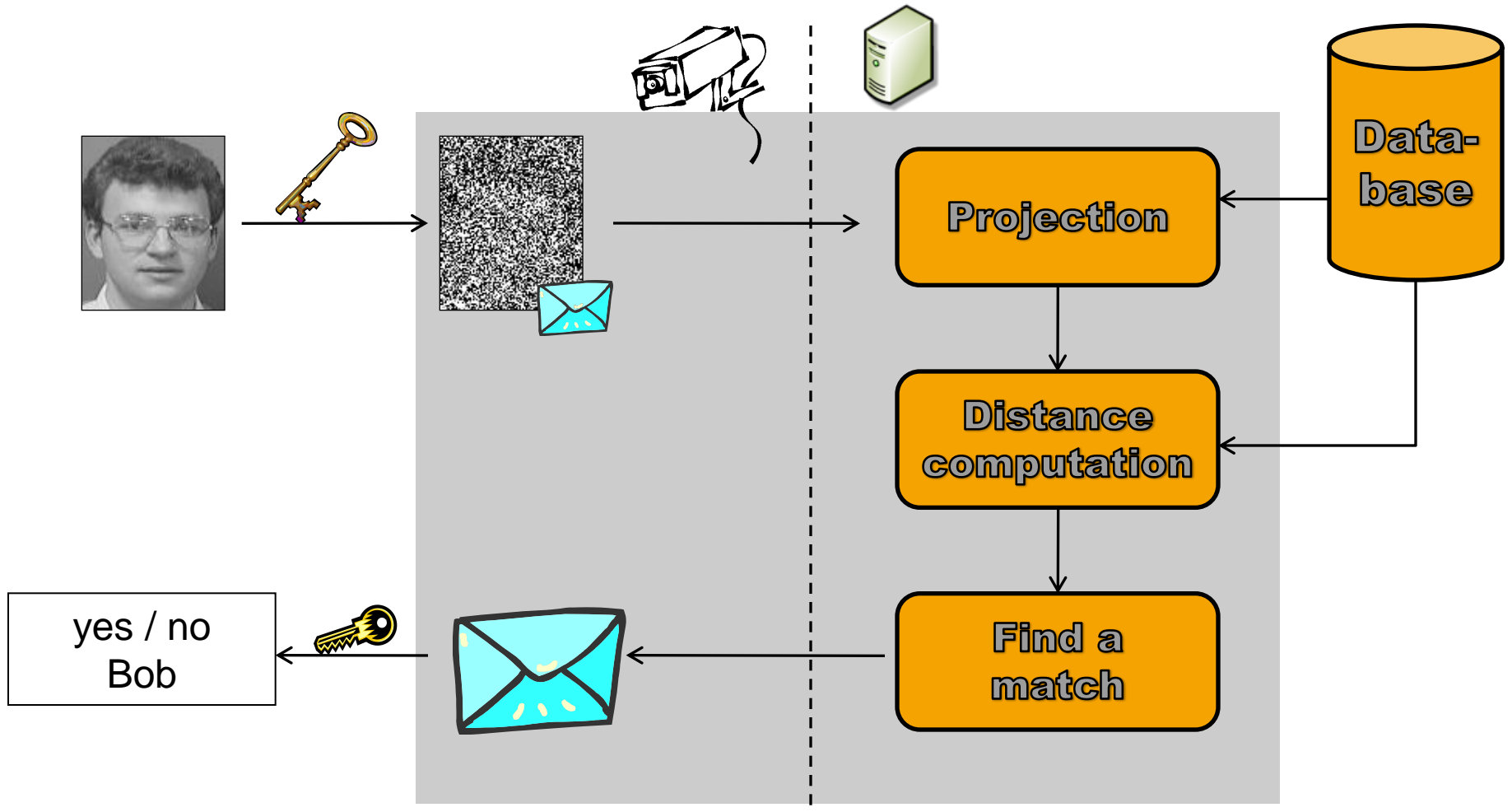
Privacy-Enhancing Technologies (PETs)

- Strike a balance between data availability and privacy
- **Paradigm:** keep data encrypted, PETs **compute with encrypted data**
- **Privacy By Design:**
Cryptographic protocols precisely limit amount of information available

- Cryptographic tools are available!
 - Homomorphic encryption
 - Yao's Garbled circuits
 - Customized protocols (private set intersection, ...)



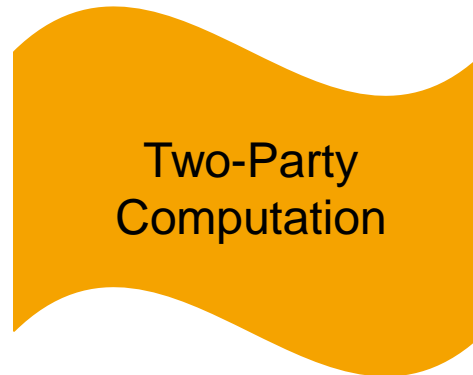
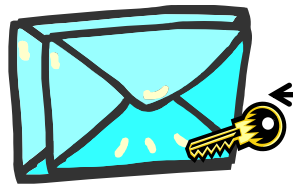
Example: Private Face Detection



Example: Private Processing of Genome Data

Physician

Bioinformatics Institute



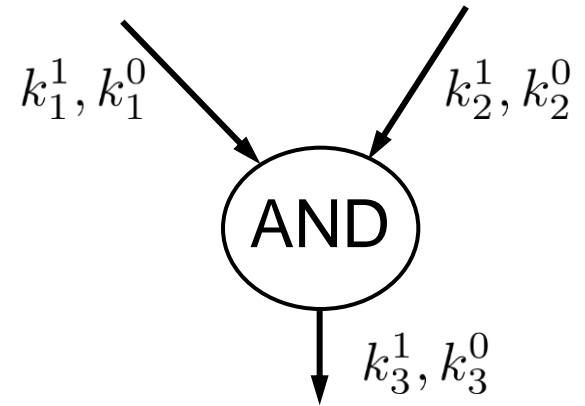
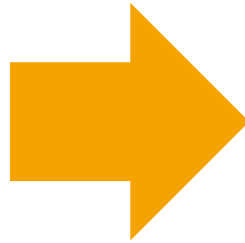
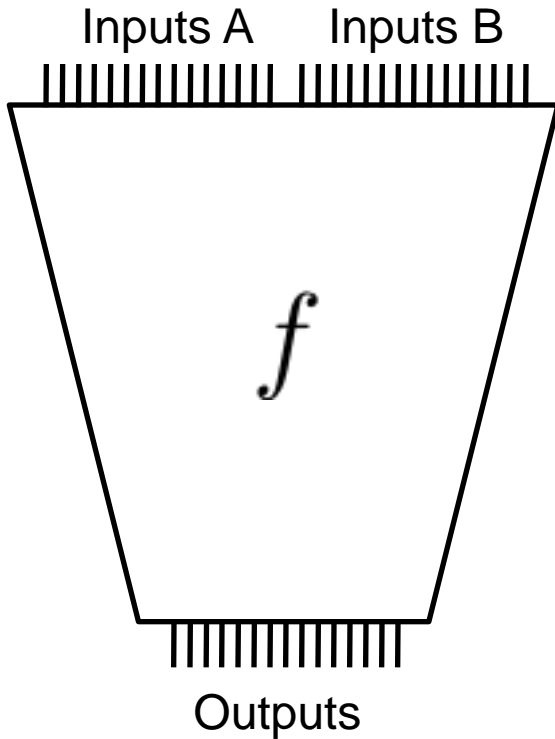
*Medical
Test*



Nice approach, but is it ready for practice?

- Cryptographic protocols are ready, **but tedious to use**
- Lack of a good tool chain that a programmer can use
- Research prototypes are available:
 - Fairplay, FairplayMP, Sharemind, Tasty
 - Fast GC frameworks (implementation support for Java)
- We need “usable” **compilers** that helps a programmer implement PETs!

Recap: Yao's garbled circuits



| \wedge | $x = 1$ | $x = 0$ |
|----------|---------|---------|
| $y = 1$ | 1 | 0 |
| $y = 0$ | 0 | 0 |

| | $x = 1$ | $x = 0$ |
|---------|-----------------------------|-----------------------------|
| $y = 1$ | $E(k_1^1, E(k_2^1, k_3^1))$ | $E(k_1^1, E(k_2^0, k_3^0))$ |
| $y = 0$ | $E(k_1^0, E(k_2^1, k_3^0))$ | $E(k_1^0, E(k_2^0, k_3^0))$ |

Our choice as basis: Bit-precise Model Checker CBMC

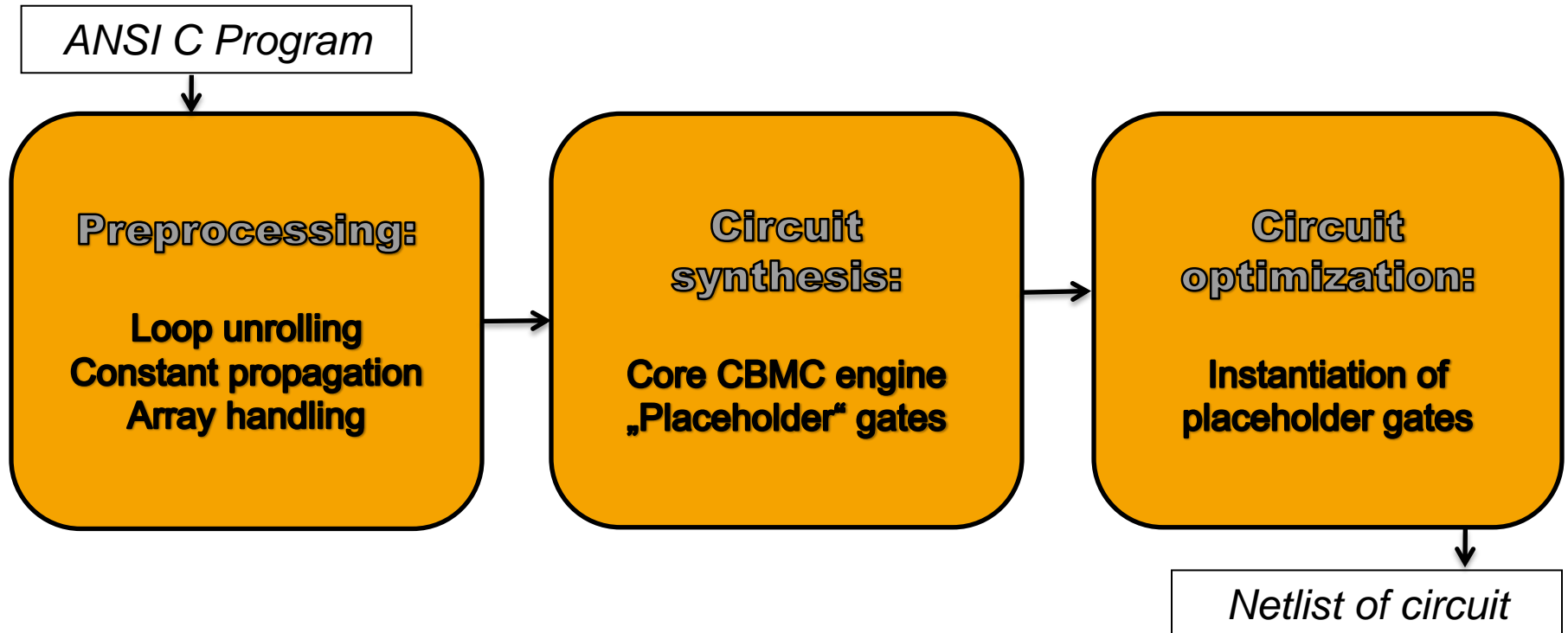
- Transforms C program into a Boolean formula
- Transformation is “bit precise”
 - ➔ models evolution of program memory



<http://www.cprover.org>

- **Bounded model checker:**
 - Unrolls program up to a fixed number of loop iterations
 - Heuristics on how much unrolling is needed
- Boolean formula consists of program model and negated property
- SAT solver checks for solution


Central idea: use transformation from C code to SAT
formula provided by CBMC for secure computing



CBMC-GC: Example, Yao's Millionaires

```
void millionaires() {  
    int INPUT_A_mila;  
    int INPUT_B_milb;  
    int OUTPUT_res;
```

Local variables code
inputs and outputs



```
    if (INPUT_A_mila > INPUT_B_milb)  
        OUTPUT_res = 1;  
    else  
        OUTPUT_res = 0;  
}
```

Computations
specified as C program



CBMC-GC: A bigger example

Matrix multiplication

```
#define S 8 // size of matrices
```

```
int INPUT_A_a[S][S];
```

```
int INPUT_B_b[S][S];
```

```
int OUTPUT_c[S][S];
```

```
void multiply()
```

```
{
```

```
    int i, j, k;
```

```
    for (i = 0; i < S; i++)
```


```
        for (j = 0; j < S; j++)
```

```
            for (k = 0; k < S; k++)
```

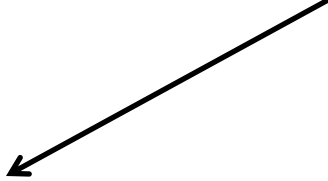
```
                OUTPUT_c[i][j] += INPUT_A_a[i][k] * INPUT_B_b[k][j];
```

```
}
```

More complex data types
like arrays, structs, enums



(Limited) support for
pointer arithmetic



CBMC-GC inherits limits from CBMC:


- **Bounded programs:** bounds for all loops must be known
→ in practice no problem
- No support for **floating point arithmetic**
- No support for **library functions** (yet)
- Limited **pointer arithmetic**
- **Integer data types** of fixed size
→ limits efficiency in secure computations

CBMC-GC: More examples

Bubblesort

```
#define K 11 // length of array
#define MEDIAN 5 // position of median
int INPUT_A_a[K];
int OUTPUT_median;
void median_bubblesort() {
    int i, j, tmp, tmp1, tmp2;
    for (i = K - 1; i > 0; i--) {
        for (j = 0; j < i; j++) {
            tmp1 = INPUT_A_a[j]; tmp2 = INPUT_A_a[j + 1];
            if (tmp1 > tmp2) {
                INPUT_A_a[j] = tmp2; INPUT_A_a[j + 1] = tmp1;
            }
        }
    }
    OUTPUT_median = INPUT_A_a[MEDIAN];
}
```

CBMC can determine
loop bounds by static analysis




CBMC-GC supports recursion

Example: Mergesort

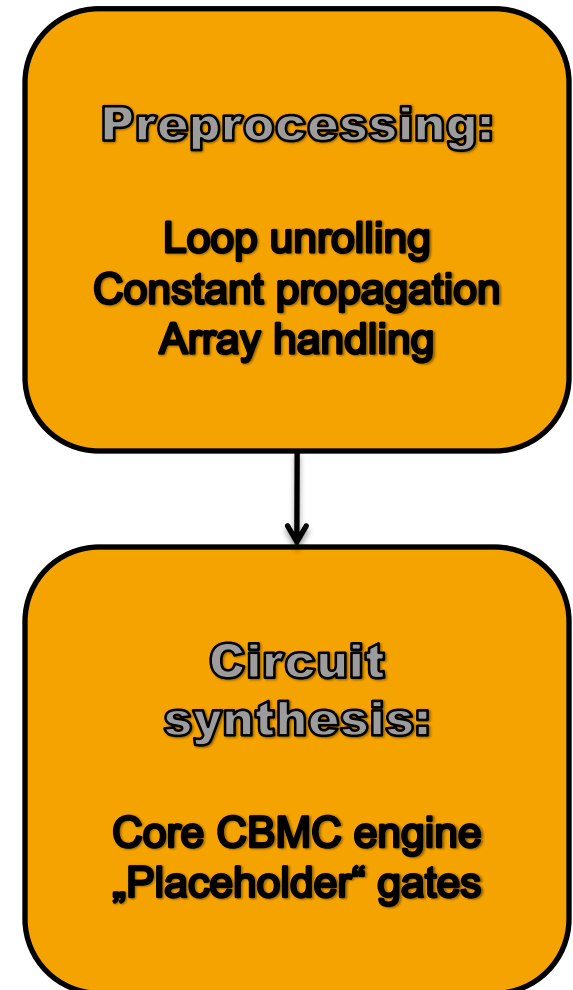
```
int b[K]; // temporary array for mergesort
void mergesort(int l, int r) {
    int i, j, k, m;
    if (r > l) {
        m = (r + l)/2; mergesort(l, m); mergesort(m + 1, r);
        for (i = m + 1; i > l; i--)
            b[i - 1] = INPUT_A_a[i - 1];
        for (j = m; j < r; j++)
            b[r + m - j] = INPUT_A_a[j + 1];
        for (k = l; k <= r; k++) {
            if (b[i] < b[j])
                INPUT_A_a[k] = b[i]; i++;
            else
                INPUT_A_a[k] = b[j]; j--;
        }
    }
}
```

Recursion; CBMC can determine bounds by static analysis



CBMC-GC: Optimizations

- Array access are slow
 - requires evaluation of a MUX circuit
 - remove some by static analysis
- CBMC is optimized for SAT performance
 - introduce placeholder gates
 - later instantiation with optimized circuits
- Optimization engine extensible



Experimental results

We used CBMC-GC in conjunction with framework for execution of garbled circuits by Huang et al (USENIX 2011)

| Experiment | Number of gates | Execution time, preprocessing | Execution time, circuit evaluation |
|-----------------------------------|------------------------|-------------------------------|------------------------------------|
| 3000 random arithmetic operations | 2,298,441 (608,668) | 970 ms | 9,774 ms |
| 8x8 matrix multiplication | 3,257,345 (905,728) | 680 ms | 18,173 ms |
| Median, bubble sort, 31 elements | 149,040 (45,120) | 733 ms | 1,644 ms |
| Median, merge sort, 31 elements | 1,339,084 (436,916) | 660 ms | 3,790 ms |

Conclusions

- Automatic compilation of two-party protocols is indeed possible
- Not as fast as hand-written code, but nevertheless usable in practice
- Will hopefully stimulate research in optimization issues, separates crypto functionality from compiler design
- Future research: other basic tools, other languages, optimizations, overcoming current limitations of CBMC-GC, ...



To come:

<http://forsyte.at/software/cbmc-gc/>