Easily programmable secure multi-party computation on integers, strings and floating point numbers

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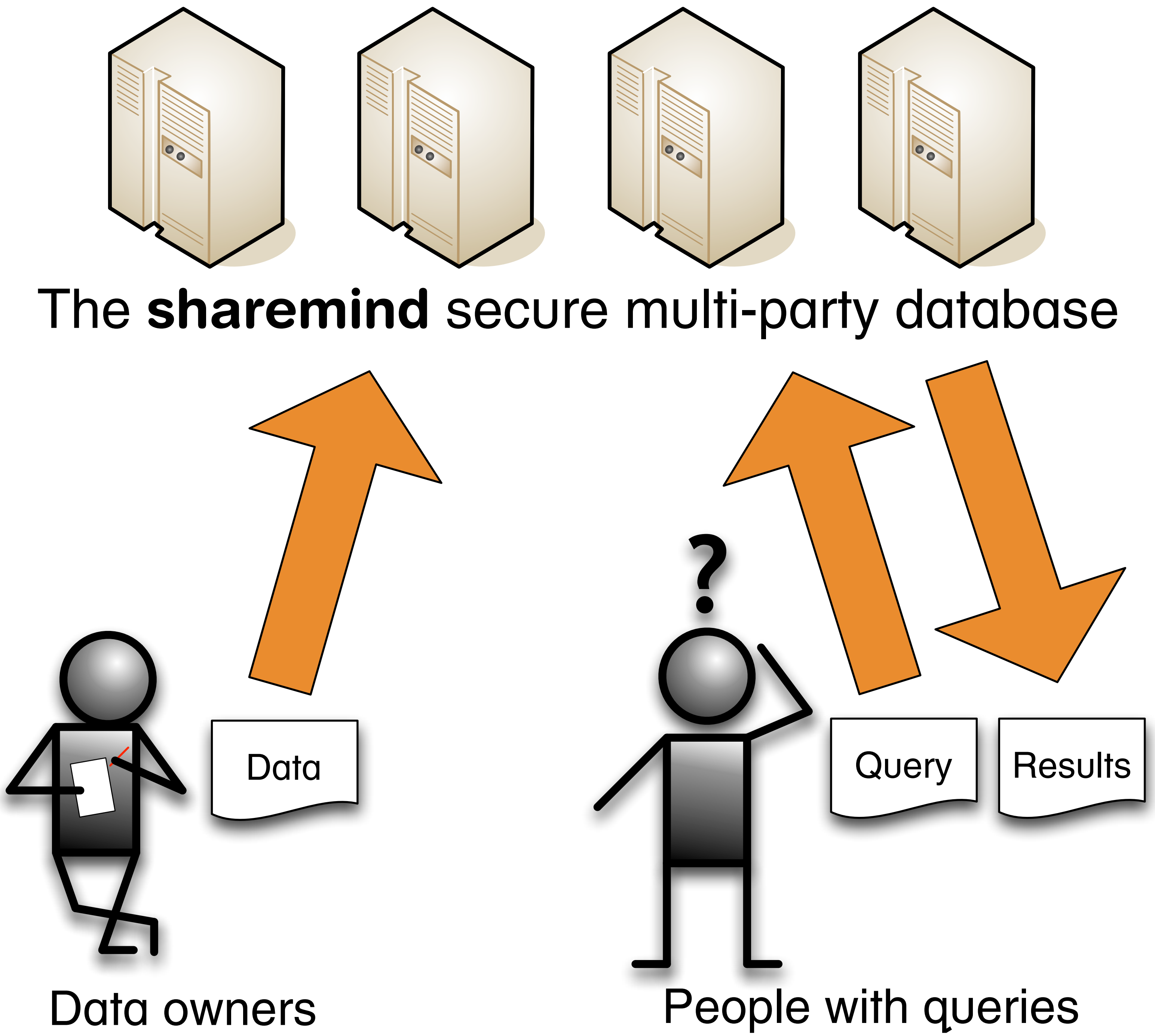
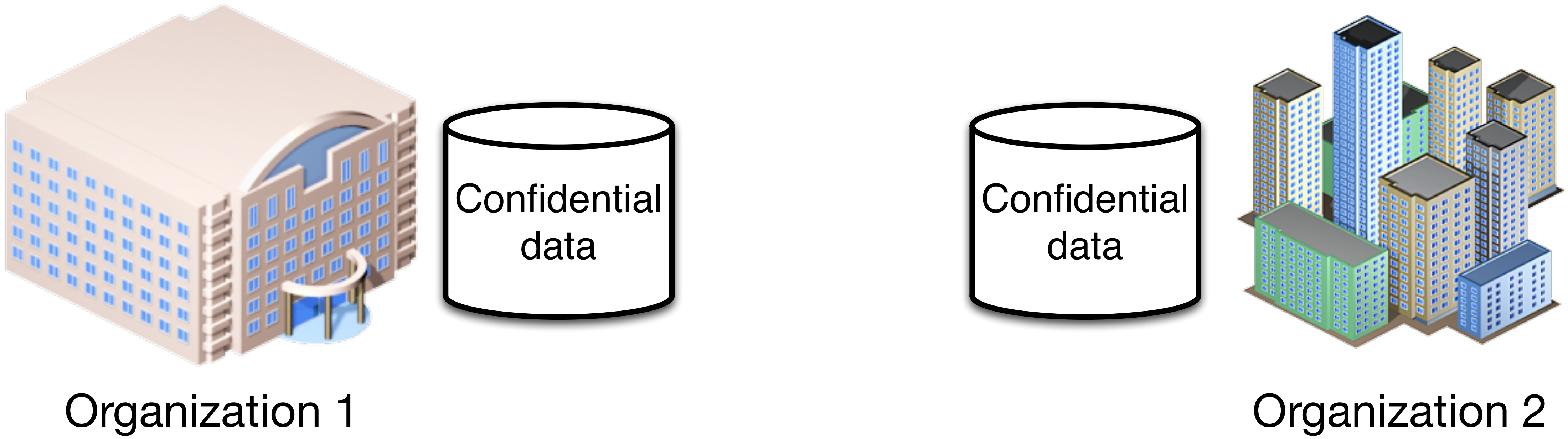
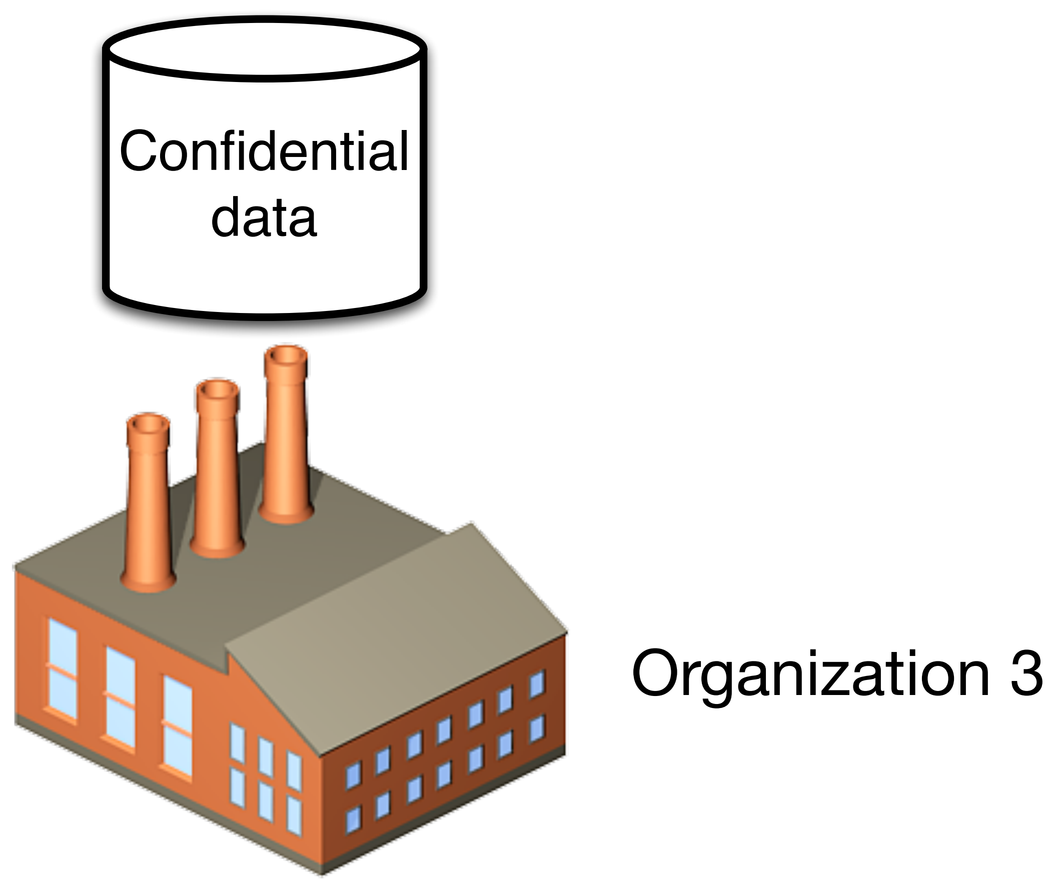
privacy preservation in statistics and data mining

Providing Security-as-a-Service



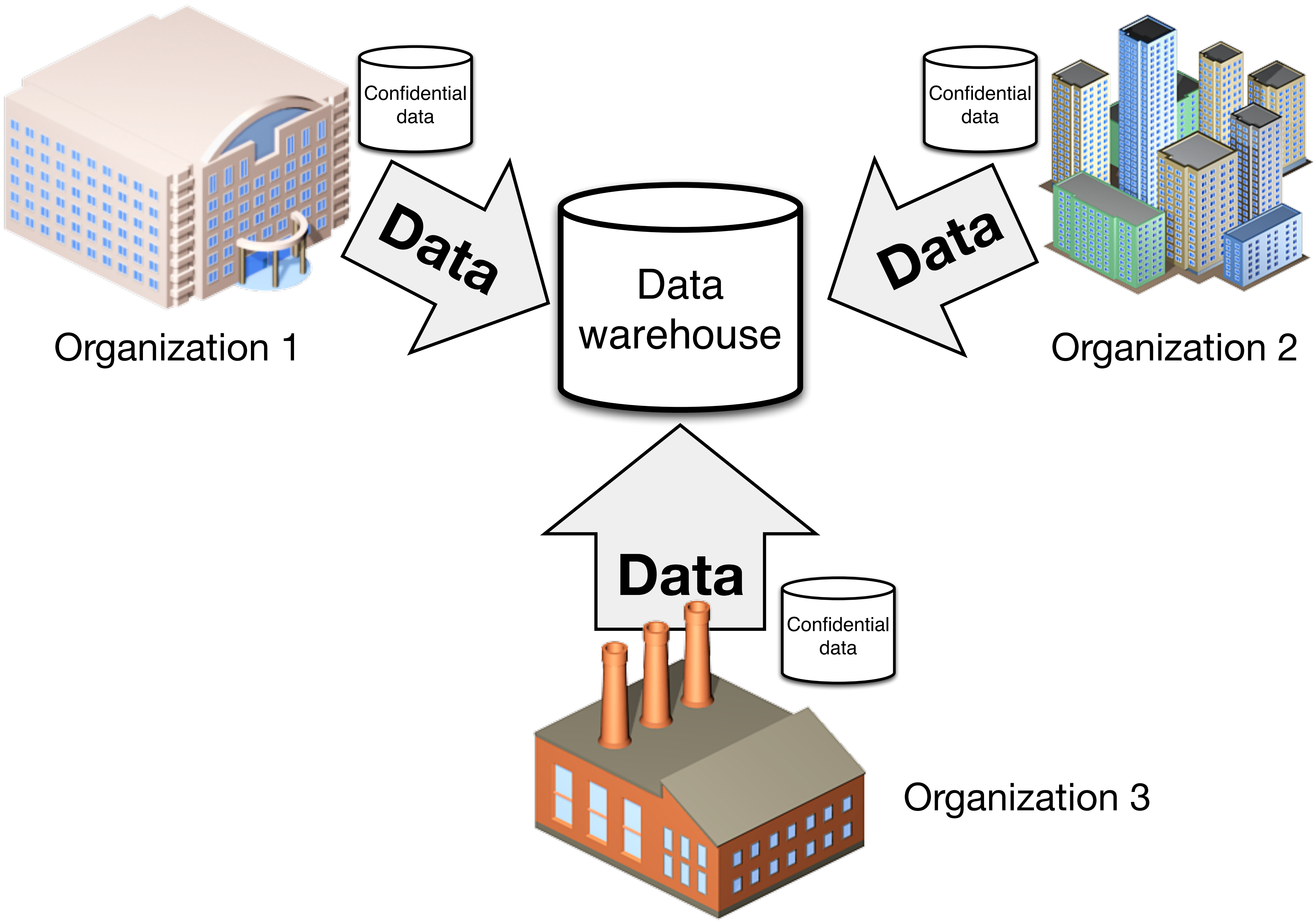
A typical problem statement



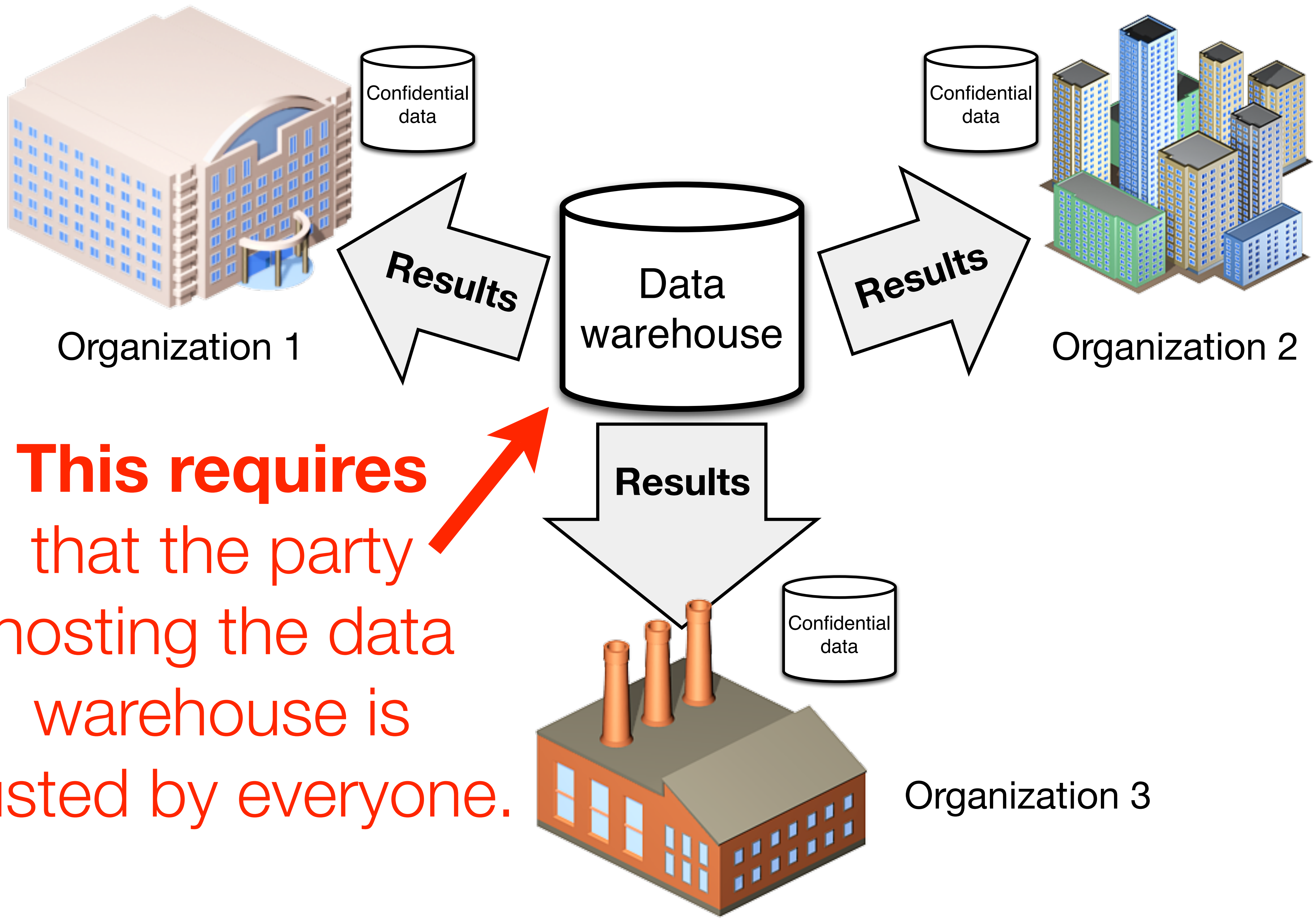


How do we
jointly analyze data
without showing
it to others?

A typical (but insecure) solution



A typical (but insecure) solution



This requires that the party hosting the data warehouse is trusted by everyone.

Our specific goal

- **Secure data aggregation**
  - Analyze data collected from several sources
  - Build services that package this technology.
- **Simple statistics and complex algorithms**
  - Compute sums and averages, use filtering.
  - Perform complex analyses like market basket analysis, clustering, regression and so on.

Security measures and guarantees

- **The data entry application protects input data.**
  - Only the data owner sees the input values.
- **The database of each server leaks no data.**
  - Defense against insiders (e.g. system administrators).
  - Some degree of protection against malicious hacking.
- **The servers run only agreed-to computations.**
  - Protection against malicious queries.

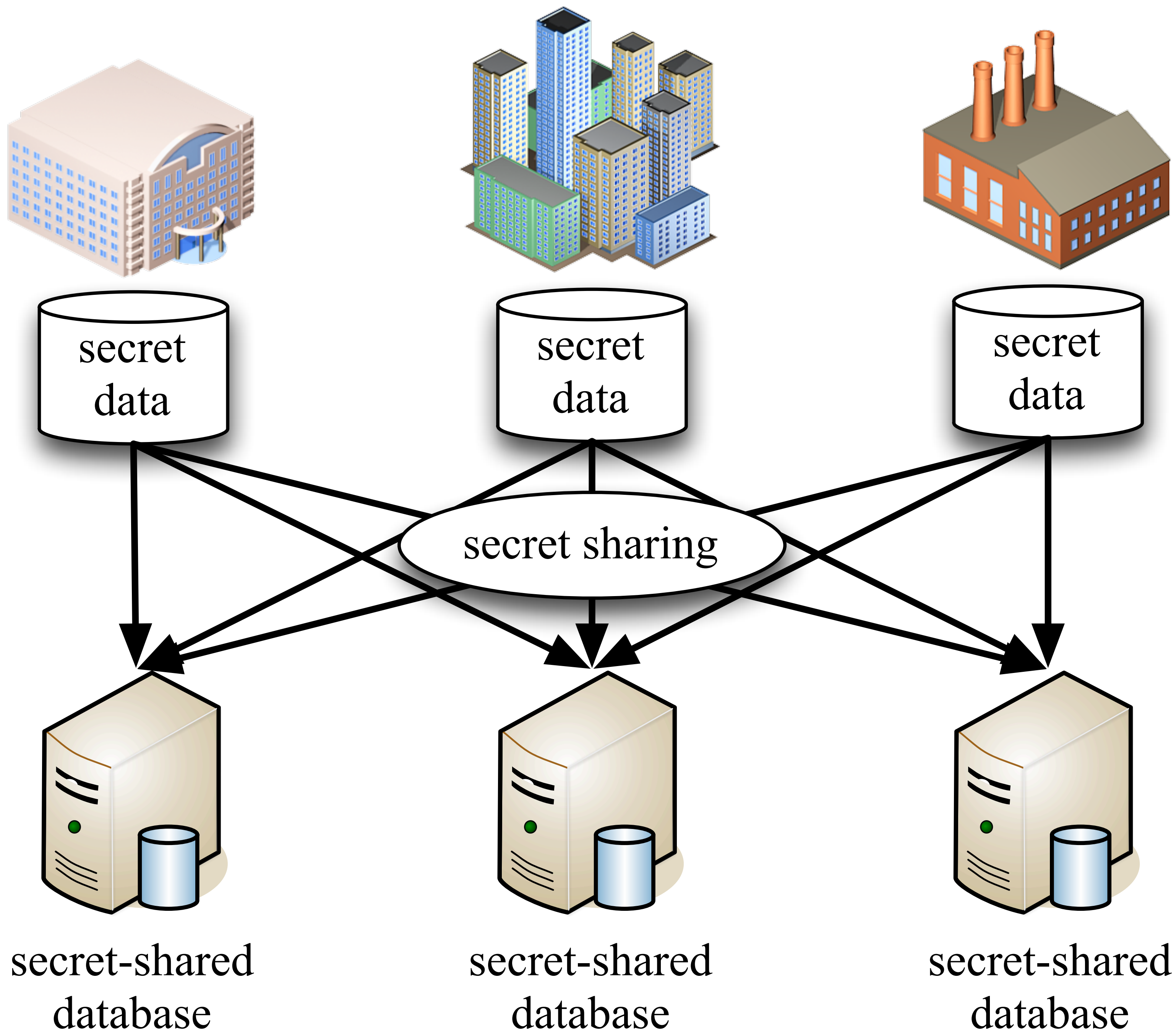
overview of sharemind 2

Secure computation à la sharemind

- We use additive secret sharing on 32-bit unsigned integers [BLW08].
- Both public and private values are from $\mathbb{Z}_{2^{32}}$.
- Three miner servers store the data and perform secure multi-party computation.
- Any number of controller applications provide data and request computations.
- Ideally, we can show information-theoretic security.

[BLW08] Bogdanov, Dan., Laur, Sven., Willemson, Jan. **Sharemind: a framework for fast privacy-preserving computations**.
In Proceedings of 13th European Symposium on Research in Computer Security, ESORICS 2008, LNCS, vol. 5283, pp. 192-206. Springer, Heidelberg (2008)

Getting data into sharemind

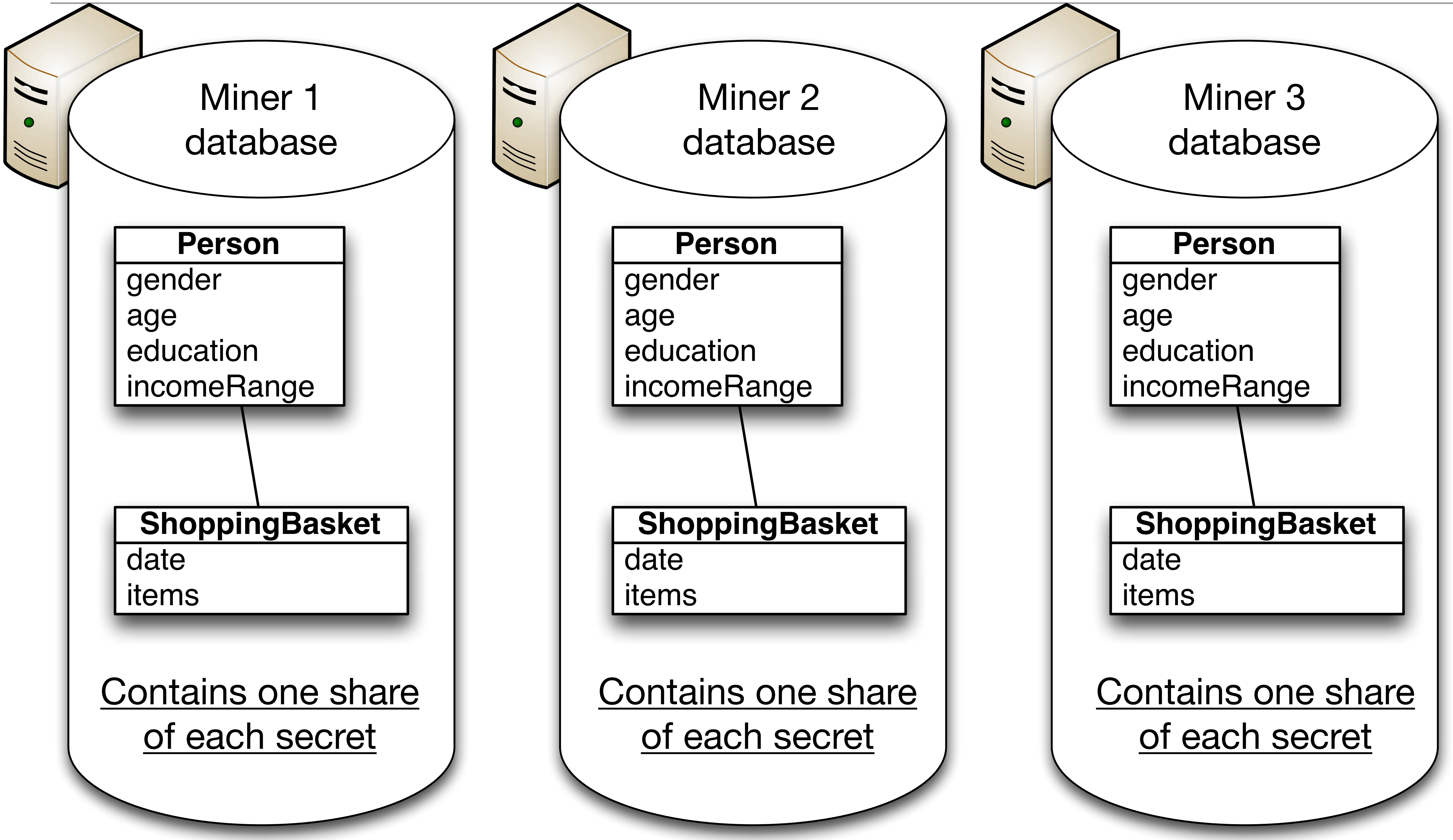


Features of controller applications

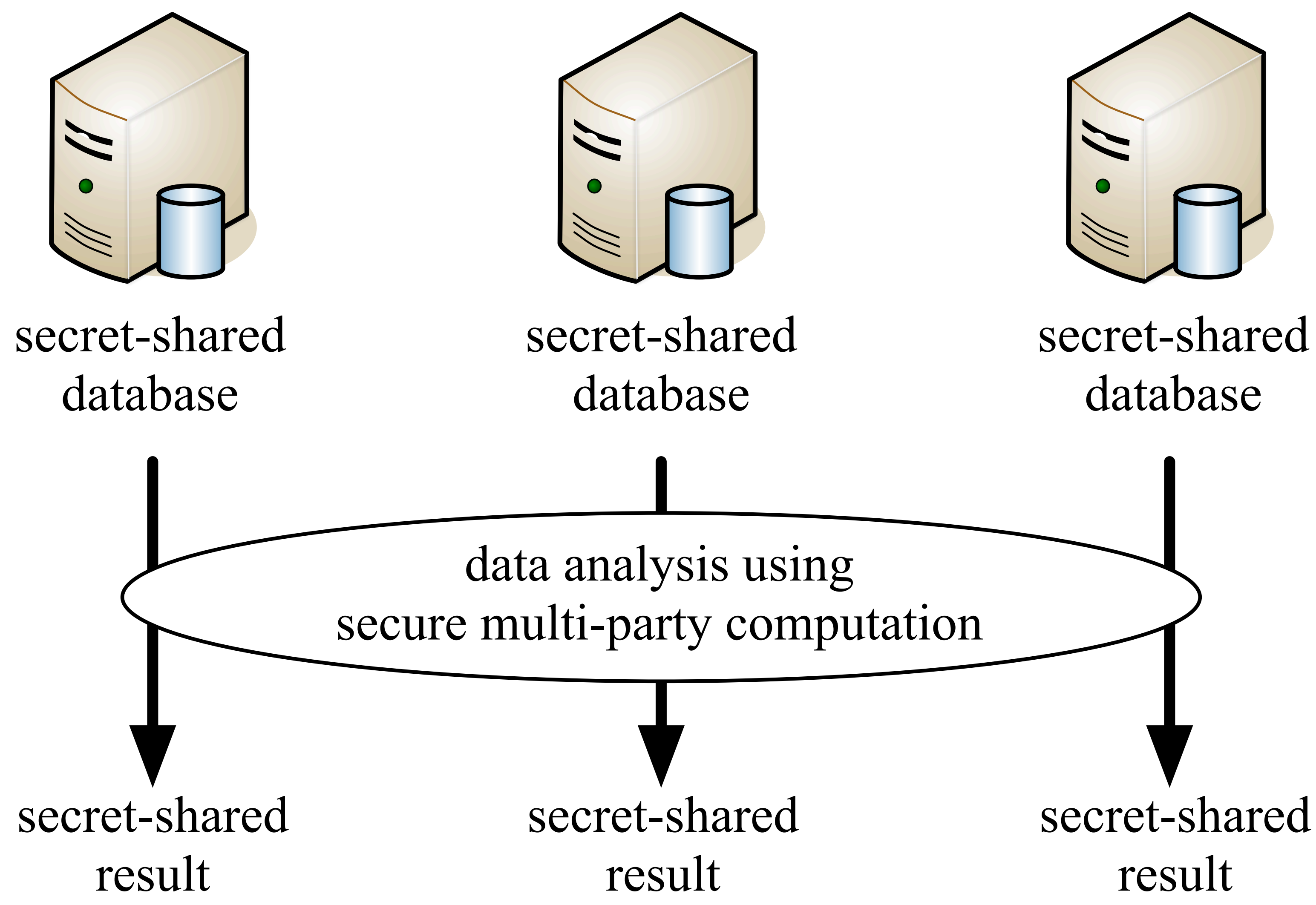
- Controller applications are built using the *controller library.*
- Different controller libraries exist for desktop and web applications [TB09].
- Mobile versions of the controller library are planned.
- The controller application automatically handles secret sharing when data is entered and when results are received.

[TB09] Talviste, Riivo., Bogdanov, Dan. **An improved method for privacy-preserving web-based data collection**. Cybernetica research report T-4-5. 2009. Available at: http://research.cyber.ee/

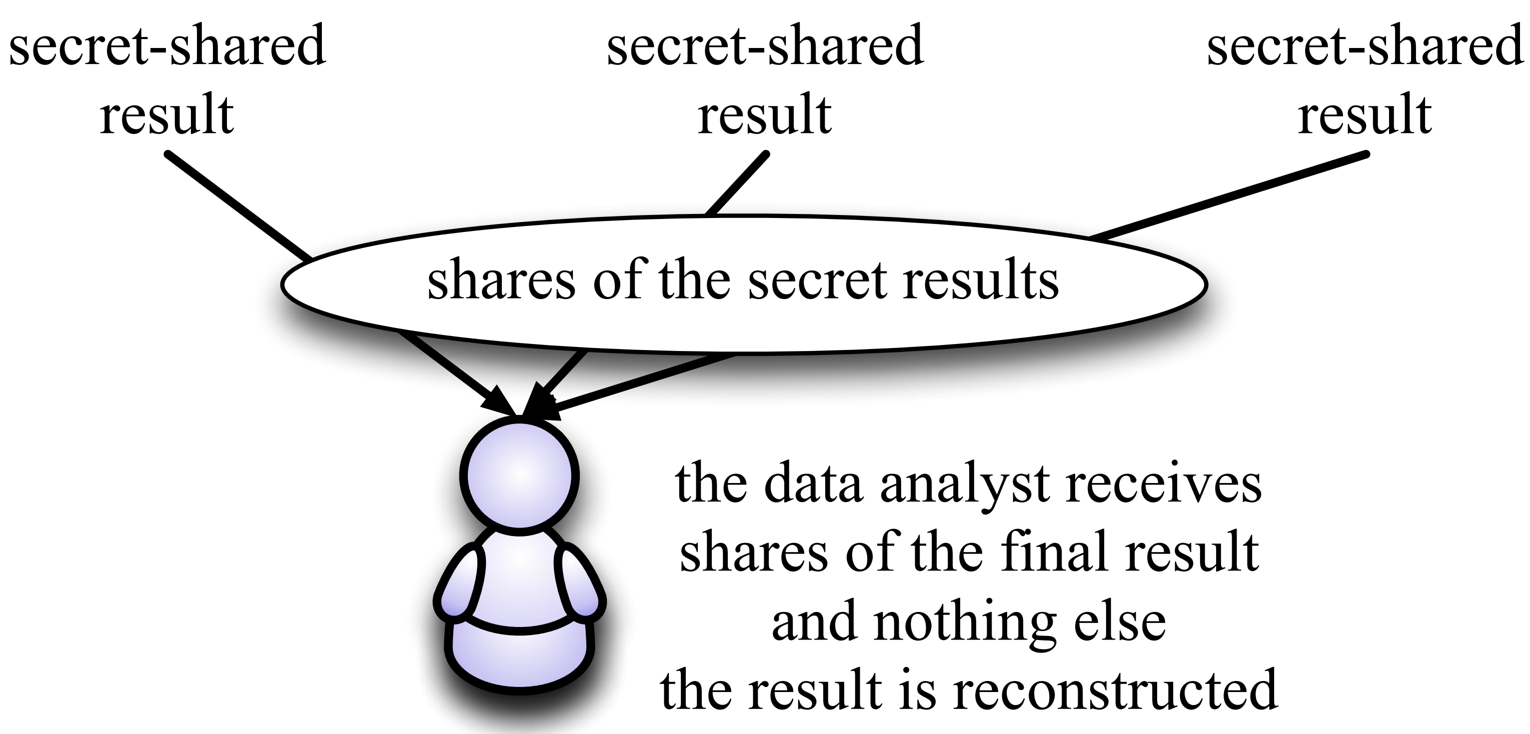
The sharemind built-in database



Processing data on sharemind



sharemind controls result publishing



Secure operations on sharemind

- Additive secret sharing is additively homomorphic so we get addition and multiplication by constant for free.
- We use custom protocols for all other operations.
- We have security and correctness proofs for these protocols together with universal composability proofs that allow them to be used in a programmable system.
- The current protocol suite is not yet published [BNTW].

[BTNW] Bogdanov, Dan., Niitsoo, Margus. Toft, Tomas.,Willemson, Jan. **High-performance secure multi-party computation for data mining applications.** Unpublished.

Performance in lab conditions (LAN)

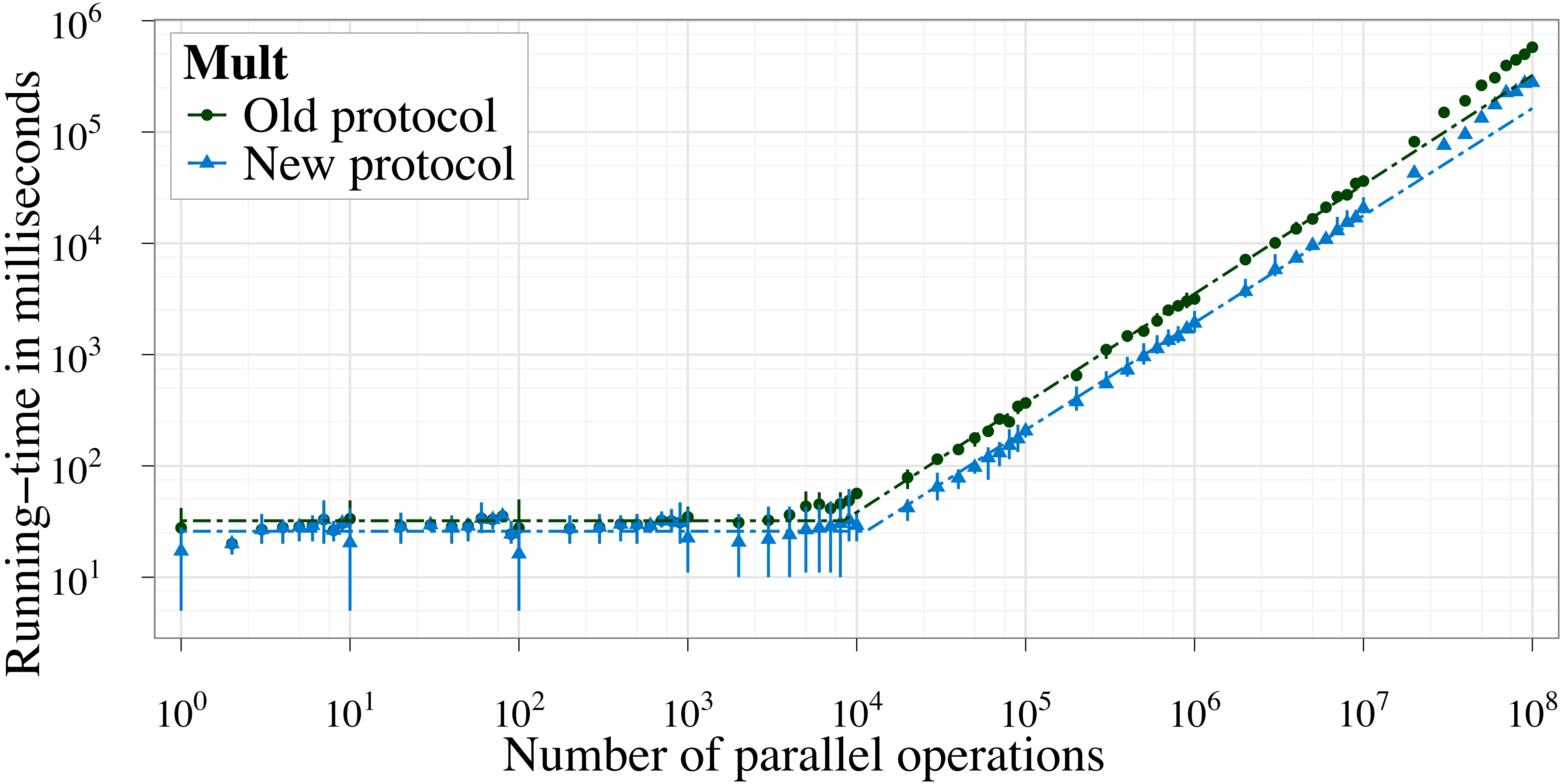
Protocol	Rounds	SISD	SIMD	SIMD Hz
Addition	local operation	-	0,015 µs	**66 MHz**
Multiplication w public	local operation	-	0,006 µs	**166 MHz**
Cast bool to int	1	15,3 ms	0,8 µs	**1,25 MHz**
Multiplication w private	2	25,9 ms	1,8 µs	**555 KHz**
Equality	$l + 2$	101 ms	5,0 µs	**200 KHz**
Greater-than	$l + 3$	113 ms	51 µs	**20 KHz**
Bit decomposition	$l + 3$	122 ms	15,7 µs	**64 KHz**
Division w public	$l + 4$	124 ms	44 µs	**23 KHz**
Division w private	$4l + 9$	390 ms	534 µs	**1,9 KHz**

Note: All operations are on 32-bit unsigned integers.

Note: $l = \log_2(numberOfBitsInDataType)$

[BTNW] Bogdanov, Dan., Niitsoo, Margus. Toft, Tomas.,Willemson, Jan. **High-performance secure multi-party computation for data mining applications.** Unpublished.

Saturation points in performance



[BTNW] Bogdanov, Dan., Niitsoo, Margus. Toft, Tomas.,Willemson, Jan. **High-performance secure multi-party computation for data mining applications.** Unpublished.

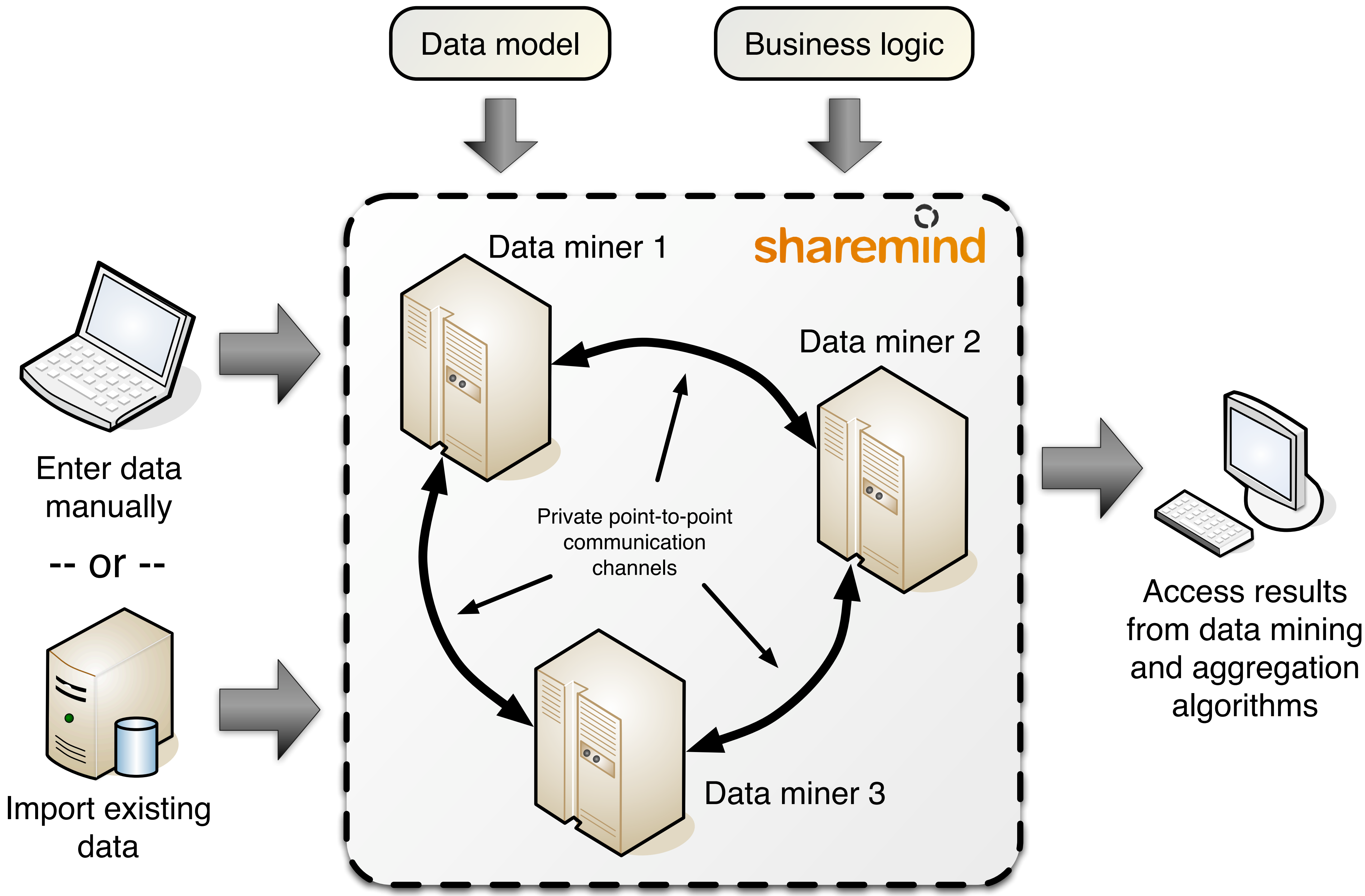
Performance on an international cloud

- We deployed Sharemind internationally, with miners in:
  - United States (West coast)
  - United Kingdom (London)
  - Japan (Tokyo)

Protocol	SIMD (100 000 parallel ops)
Cast bool to int	18 µs per operation
Multiplication w private	36 µs per operation
Equality	78 µs per operation
Greater-than	380 µs per operation
Bit decomposition	1,58 ms per operation

tools for creating secure applications

Deployment of a sharemind system



Programming secure computations

- The secure functionality is programmable in an assembly language that is interpreted by Sharemind.
- Internally, Sharemind has a private stack and public and private registers to support the implementation of algorithms.
- All registers store vectors to better support SIMD operations.
- The design is described in [BL10].

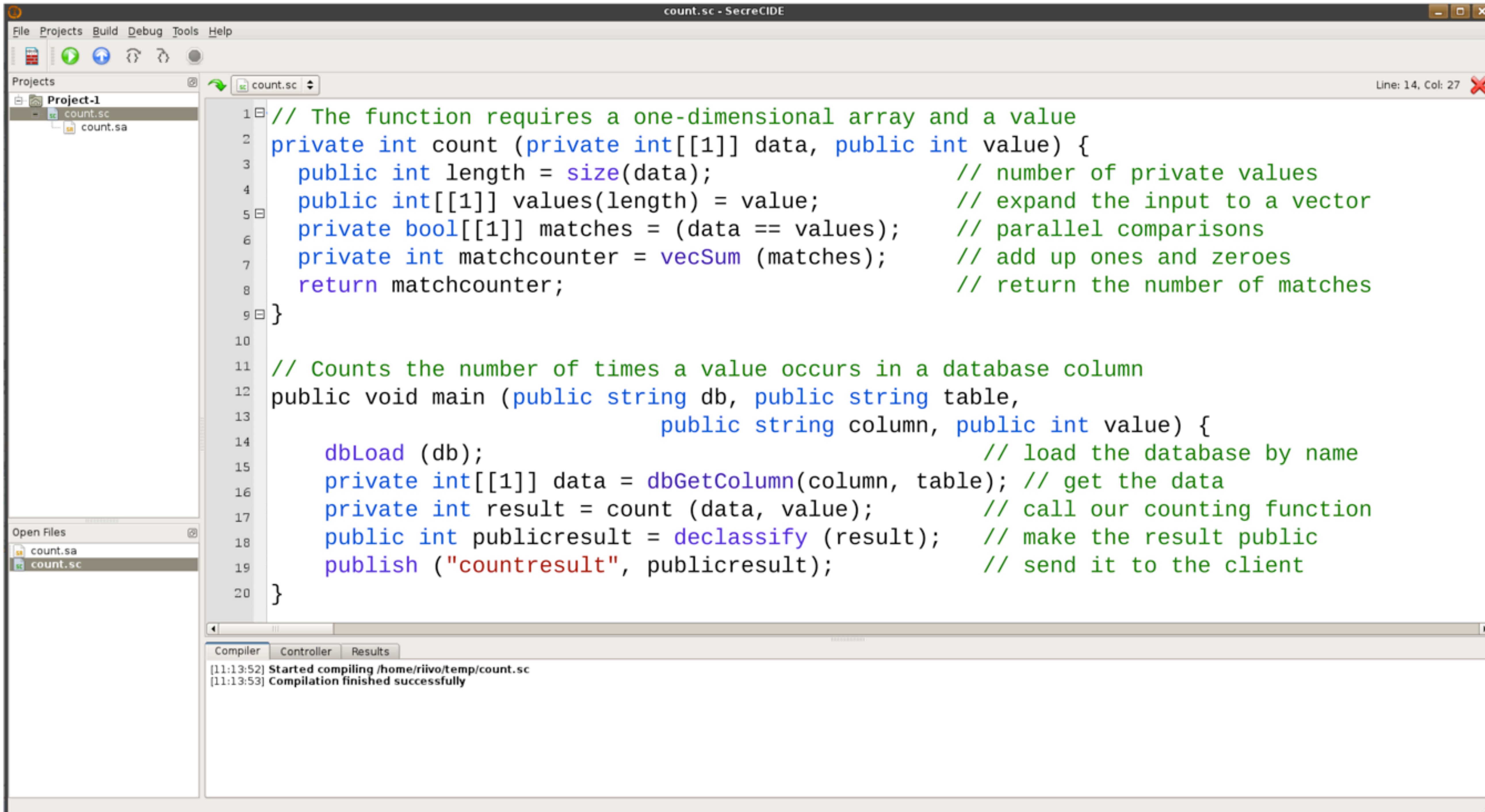
[BL10] Bogdanov, Dan; Laur, Sven. **The design of a privacy-preserving distributed virtual machine**.
In the Collection of AEOLUS theoretical findings. Deliverable D1.0.6. AEOLUS project IP-FP6-015964. 2010.

The SecreC language

```
public int count (private int[[1]] data,
                  public int value)
{
  public int length = size (data);
  private int matchcounter = 0;
  public int i = 0;
  for (i = 0; i < length; i++) {
    private bool match = (data[i] == needle);
    matchcounter += match;
  }
  return declassify (matchcounter);
}
```


[J10] Jagomägis, Roman. **SecreC: a Privacy-Aware Programming Language with Applications in Data Mining**. Master's thesis. University of Tartu, 2010.
[R10] Ristioja, Jaak. **An analysis framework for an imperative privacy-preserving programming language**. Master's thesis. University of Tartu, 2010.

The SecreCIDE developer tool



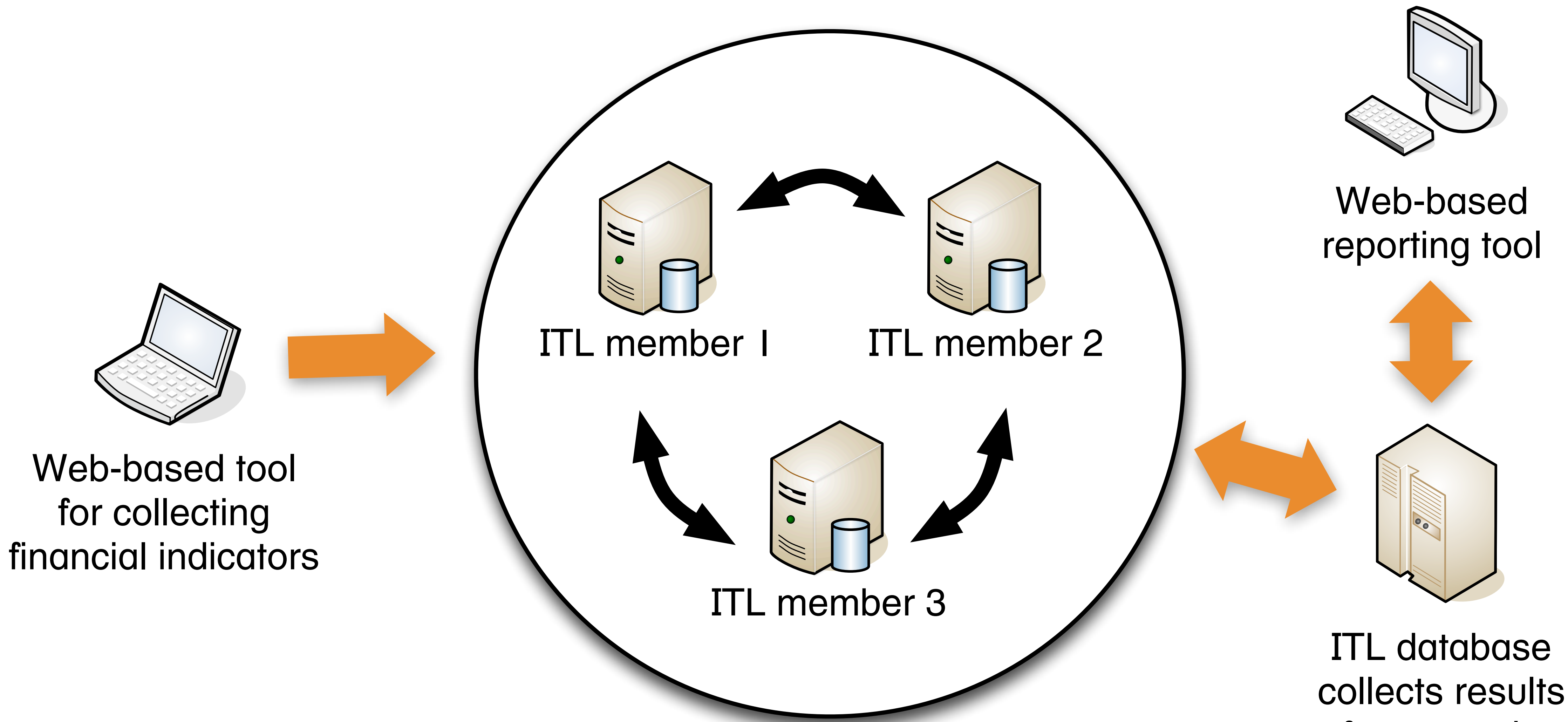
[RR10] Rebane, Reimo. **An integrated development environment for the SecreC programming language**. Bachelor's thesis. University of Tartu, 2010.

The sharemind SDK is freely available

- Sharemind SDK version 2012.04 is the latest version.
- It contains:
  - a developer version of the Sharemind 2.1 machine,
  - a compiler for the SecreC programming language,
  - a controller library for C++ applications,
  - example SecreC code and applications
- See https://sharemind.cyber.ee/ for downloads.

applications

sharemind in financial data analysis



A Sharemind installation deployed by
three independent members of the
ITL consortium performs secure computations

[BTW12] Bogdanov, Dan., Talviste, Riivo. Willemson, Jan. **Deploying secure multi-party computation for financial data analysis (Short Paper)**. In Proceedings of the Sixteenth International Conference on Financial Cryptography and Data Security 2012. To appear.

Secure computation algorithms used

- The analyses were implemented in SecreC.

Analysis operation	**Applied secure computation primitives**
Oblivious filtering to process only values that were entered by the user.	Boolean values, integer values, casting booleans to integers, multiplication.
Sorting individual data vectors	Oblivious array sorting using a sorting network. Requires addition, multiplication, and comparison.
Calculating a composite indicator *added value per employee*	Division of secret values
Time series for financial indicators	Oblivious matrix sorting by a key column

[BTW12] Bogdanov, Dan., Talviste, Riivo. Willemson, Jan. **Deploying secure multi-party computation for financial data analysis (Short Paper)**. In Proceedings of the Sixteenth International Conference on Financial Cryptography and Data Security 2012. To appear.

[LZW11] Laur, Sven., Zhang, Bingsheng., Willemson, Jan. **Round-efficient Oblivious Database Manipulation.** In Proceedings of the 14th International Conference on Information Security, ISC 2011, LNCS, vol. 7001, pp. 262-277. Springer, Heidelberg (2011)

Frequent itemset mining

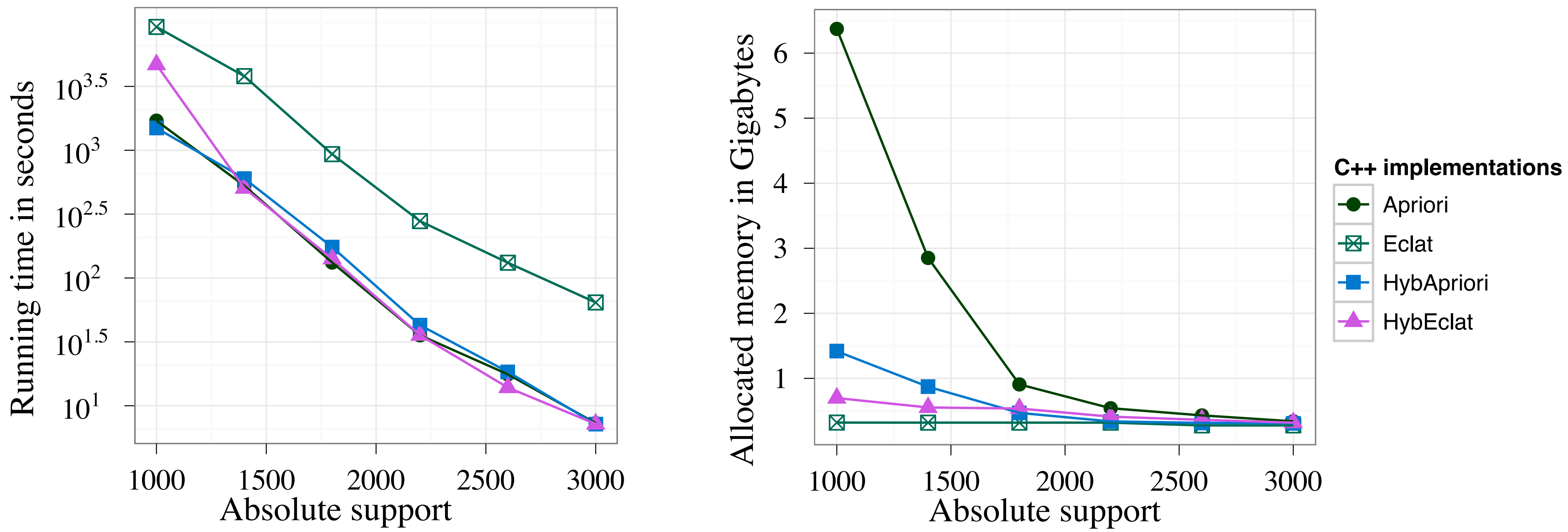
- FIM and association mining are used in problems like collaborative filtering and shopping basket analysis.
- We implemented four frequent itemset mining algorithms on Sharemind (Apriori, Eclat and hybrids).
- We benchmarked the result on three datasets.

Dataset	Transactions	Items	Density
mushroom	8124	119	19,3%
chess	3196	75	49,3%
retail	88163	16470	0,06%

[BJL12] Bogdanov, Dan., Jagomägis, Roman. Laur, Sven **A universal toolkit for cryptographically secure privacy-preserving data mining**. In Proceedings of the Pacific Asia Workshop on Intelligence and Security Informatics 2012. To appear.

sharemind processing large data

- To find frequent 11-item sets with support 2000 from the mushroom dataset Apriori needs to perform:
  - 71 548 068 secure multiplications
  - 8 926 secure greater-than comparisons



[BJL12] Bogdanov, Dan., Jagomägis, Roman. Laur, Sven **A universal toolkit for cryptographically secure privacy-preserving data mining**. In Proceedings of the Pacific Asia Workshop on Intelligence and Security Informatics 2012.

introducing
sharemind 3

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Adding more integer types

- The 32-bit integer type was hardcoded in Sharemind 2.
- However, our arithmetic protocols work in $\mathbb{Z}_{2^{2^n}}$.
- Therefore, we can let the applications use booleans, 8-bit integers, 16-bit integers and 64-bit integers too.
- Smaller integers are more efficient since they use less communication and storage space.
- Currently, we have used unsigned integers, but we could adapt some of the protocols to signed integers.

Moving from integers to real numbers

- Given that we now have secret values with different bit depths, we can consider more complex data types.
- Our first target is to suppert floating point numbers.
- The standard IEEE 754 32-bit floating point number looks like this:

- In Sharemind 3, we will use a modified version:

[WK12] Willemson, Jan., Kamm, Liina. **Secure Multiparty Floating Point Arithmetic.** Submitted.

Operations on floating point numbers

- We created data-independent circuits for adding and multiplying secret-shared floating point numbers.
- We do not process Not-a-Number cases. The protocols will not leak anything, but the result is undefined.
- After implementing addition and multiplication, we used Taylor series to compute basic functions such as sine, natural logarithm and square root.

[WK12] Willemson, Jan., Kamm, Liina. **Secure Multiparty Floating Point Arithmetic.** Submitted.

Benchmarks on floating point ops

- An unoptimized addition takes 1.4 seconds.
- An unoptimized multiplication takes 0.4 seconds.
- Sine computation (5 elements) takes 8.8 seconds.
- Natural logarithm (6 elements) takes 13.5 seconds.
- Square root (5 elements) takes 10.1 seconds.
- All operations will be more efficient if parallelized.

[WK12] Willemson, Jan., Kamm, Liina. **Secure Multiparty Floating Point Arithmetic.** Submitted.

Private string operations

- Given that we have different bit depth integers, we can use their arrays to implement ASCII and UTF strings.
- We can have two options for strings:
  - fixed length - potentially hides message length
  - variable length - string is as long as the array allocated for its storage
- Algorithms are slightly different for both cases.

Challenges for string algorithms

- Character manipulation, especially with UTF strings, requires bit-level operations to be efficient.
- However, if we use additive secret sharing, we need to use an expensive bit decomposition to manipulate bits.
- Therefore, for strings we will consider using XOR instead of addition in the secret sharing scheme.
- The same approach is useful also for other operations that need bit-level access to data - like secure AES.

[LTW12] Laur, Sven., Talviste, Riivo., Willemson, Jan. **AES block cipher implementation and secure database join on the Sharemind secure multi-party computation framework**. Submitted.

Challenges for string algorithms

- Standard string algorithms can make decisions based on the data and jump ahead (eg. in searching).
- To guarantee data independence, we often need to run naïve versions of algorithms and brute force searches
- However, brute force can typically be heavily parallelized with SIMD operations.
- The alternative is to leak some (possibly aggregated) bits about the string's contents, but such decisions should be driven by applications.

Adding support for new paradigms

- Sharemind 2 is limited to three parties and solutions based on secret sharing. The limits will be removed.
- However, there are interesting protocols and primitives out there that may work in the same application model:
  - Homomorphic encryption can help reduce the number of required servers and the communication.
  - Security in the consistent or malicious model will help protect against outages and hacking.
- We will be happy to implement interesting protocols.

Keeping it all easy for the developers

- We want all new data types to be available in the SecreC language for ease of use.
- We want the programming experience to be similar to existing techniques. Sharemind should be perceived similarly to a database and application server.
- Programs written in SecreC should be forward-compatible with new results in cryptography.
- The Sharemind machine is responsible for hiding the complexities of scheduling protocols.

Future work

- In the coming years we will be looking for novel practical protocol designs for inclusion in Sharemind.
- We want to extend the practical applicability of secure computation technology by building more prototypes.
- The technology can be used to solve real-life problems and we will jump to the opportunity of doing so.
- We will maintain a freely available toolkit for creating secure computation applications for academic use.
- We welcome all collaboration opportunities.

sharemind

https://sharemind.cyber.ee/

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