Privately Evaluating Decision Trees and Random Forests

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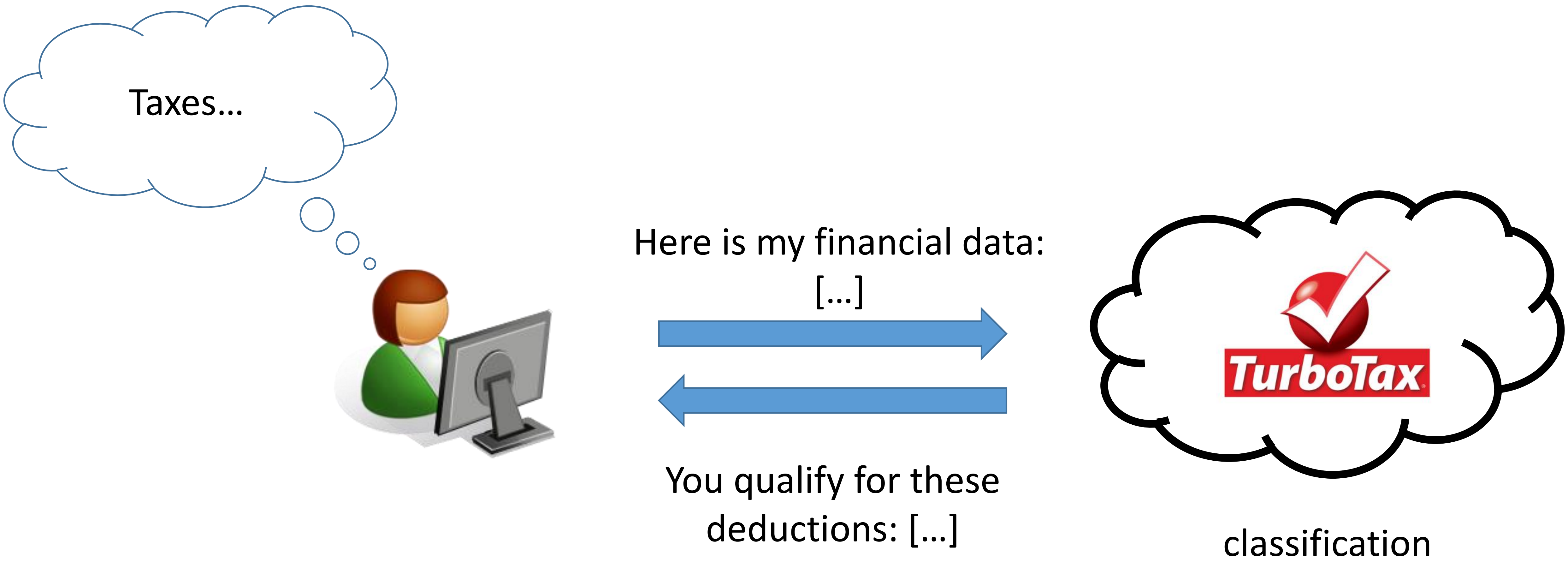
Motivations



The Power of the Cloud

Advantage of the cloud: *big data*

But can now the cloud be trusted?

- Financial Records
- Medical Records
- Legal Records
- Personal Information

Privacy-Preserving Machine Learning

Leverage the power and data available in cloud-based services

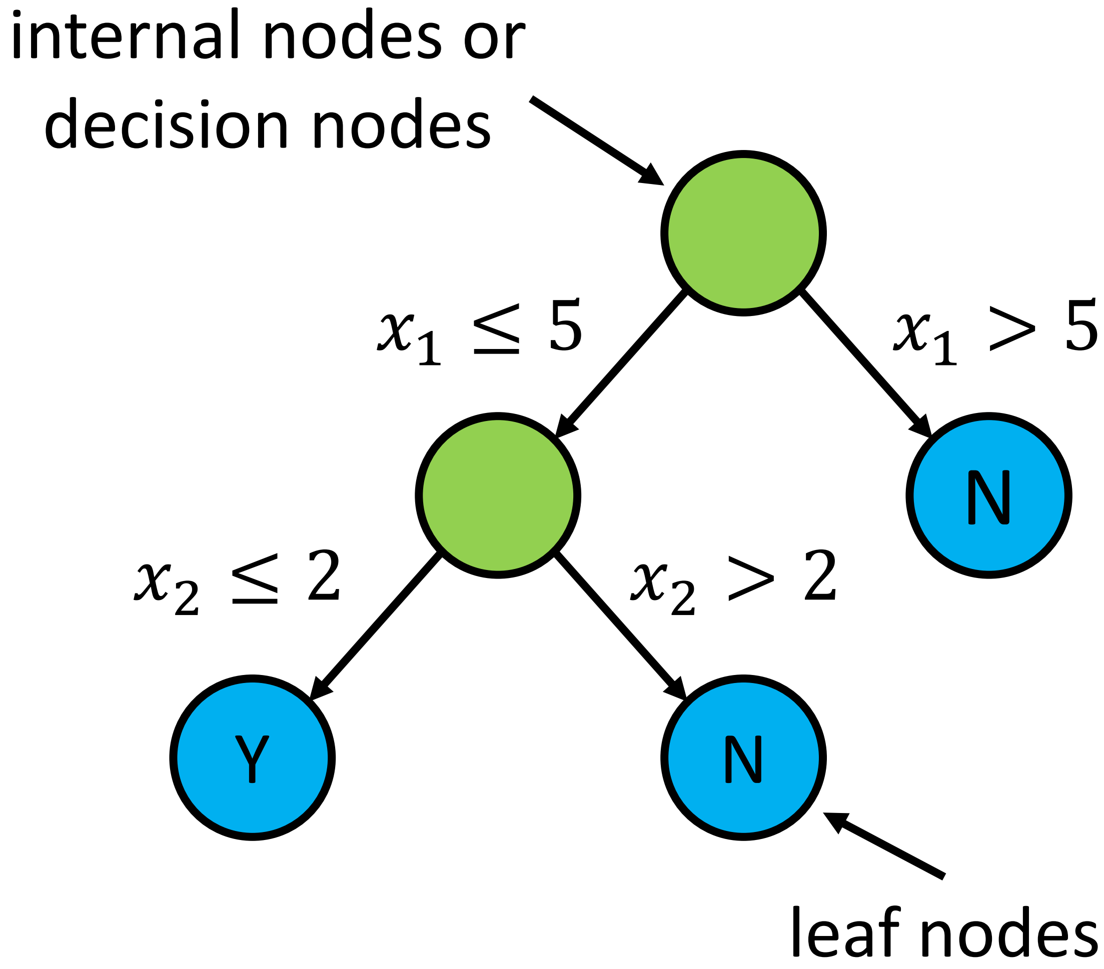
Preserve user privacy

Scope of This Talk

Consider one particular model: decision trees and their generalization, random forests

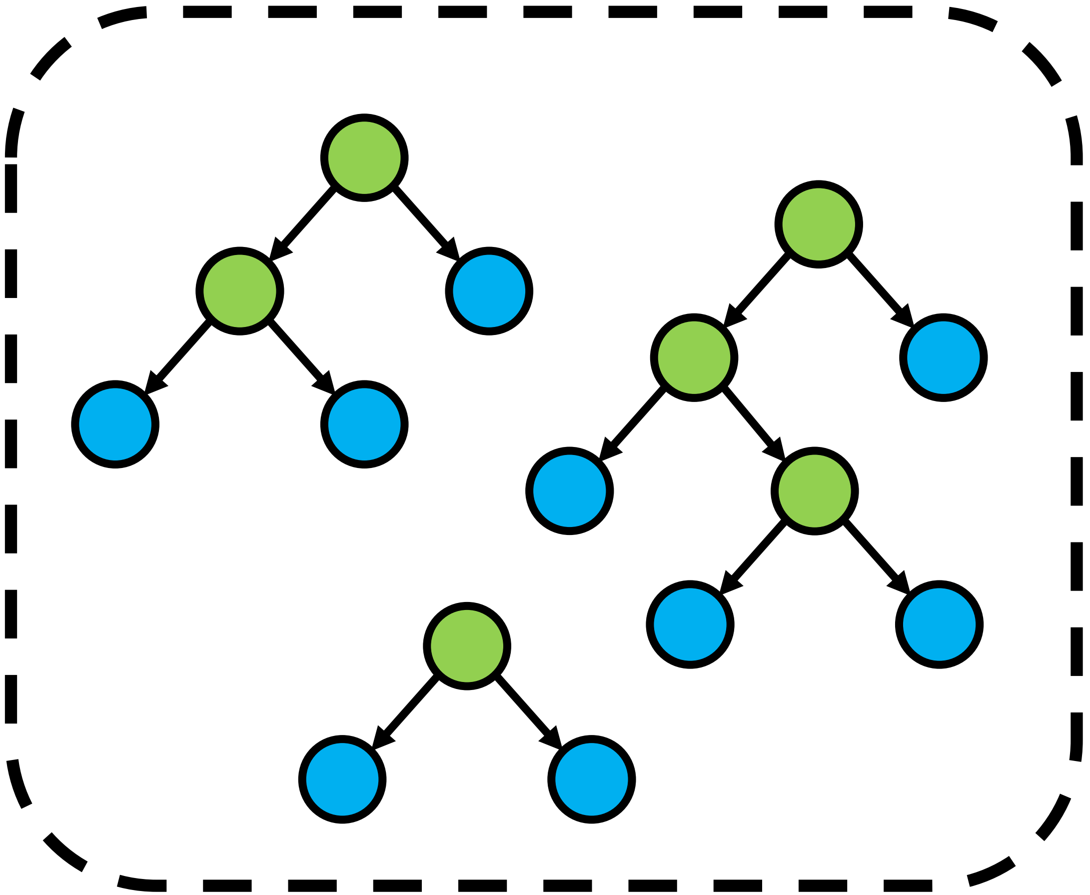
Assume that the server already has the model: focus on *private evaluation* of models

Decision Trees



- Nonlinear models for regression or classification
- Consists of a series of decision variables (tests on the feature vector)
- Evaluation corresponds to tree traversal

Random Forests



- Train many decision trees on random subsets of the features
- Output is average (majority) of outputs of individual decision trees for regression (classification)
- Reduces variance of model

Security Model

Semi-honest adversary: follow the protocol as written, but may try to learn additional information from the protocol trace (*honest-but-curious*)

Malicious adversary: can deviate arbitrarily from the protocol to satisfy its objectives

Server-Side and Client-Side Privacy

Privacy for the client: server learns no information about the client's query

Privacy for the server: client does not learn anything about the model other than what s/he already learns from the output

Formally, we use the real-world / ideal-world paradigm

Comparison Protocol

Comparison Protocol [DGK07, BPTG14]

Recall decision tree setting:

- Server has a decision tree (the model)
- Client has feature vector

Comparison Protocol [DGK07, BPTG14]

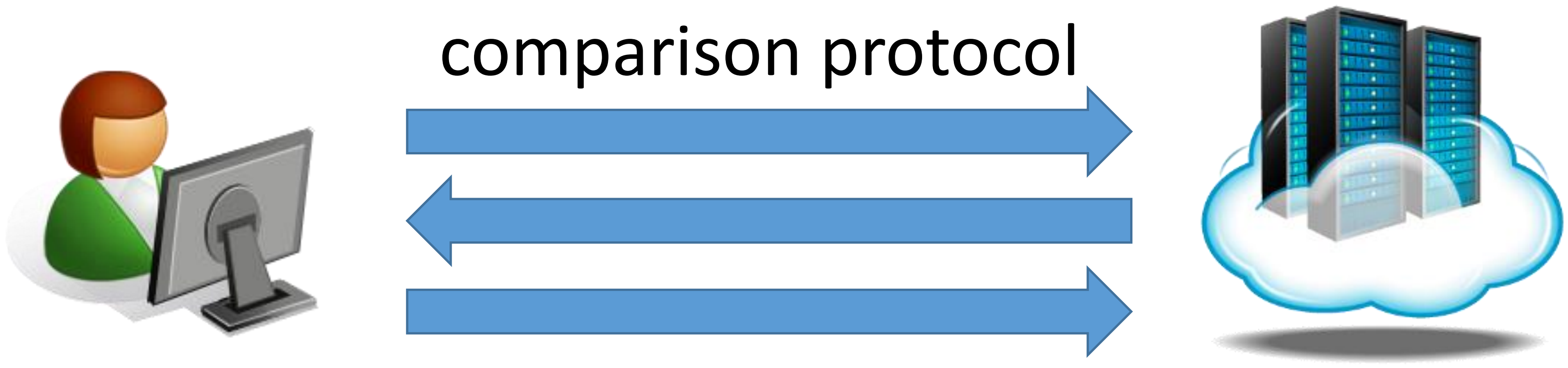
Basic building block for decision trees: evaluating comparisons of the form

$$\mathbf{1}\{x_{i_k} < t_k\}$$

index into feature vector (x_{i_k} is the client's input)

threshold (server's input)

Comparison Protocol [DGK07, BPTG14]



client input: x

server input: y

Desired functionality:

Server learns an *encryption* of comparison bit (under the client's public key), client learns nothing

Back to the Comparison Protocol…

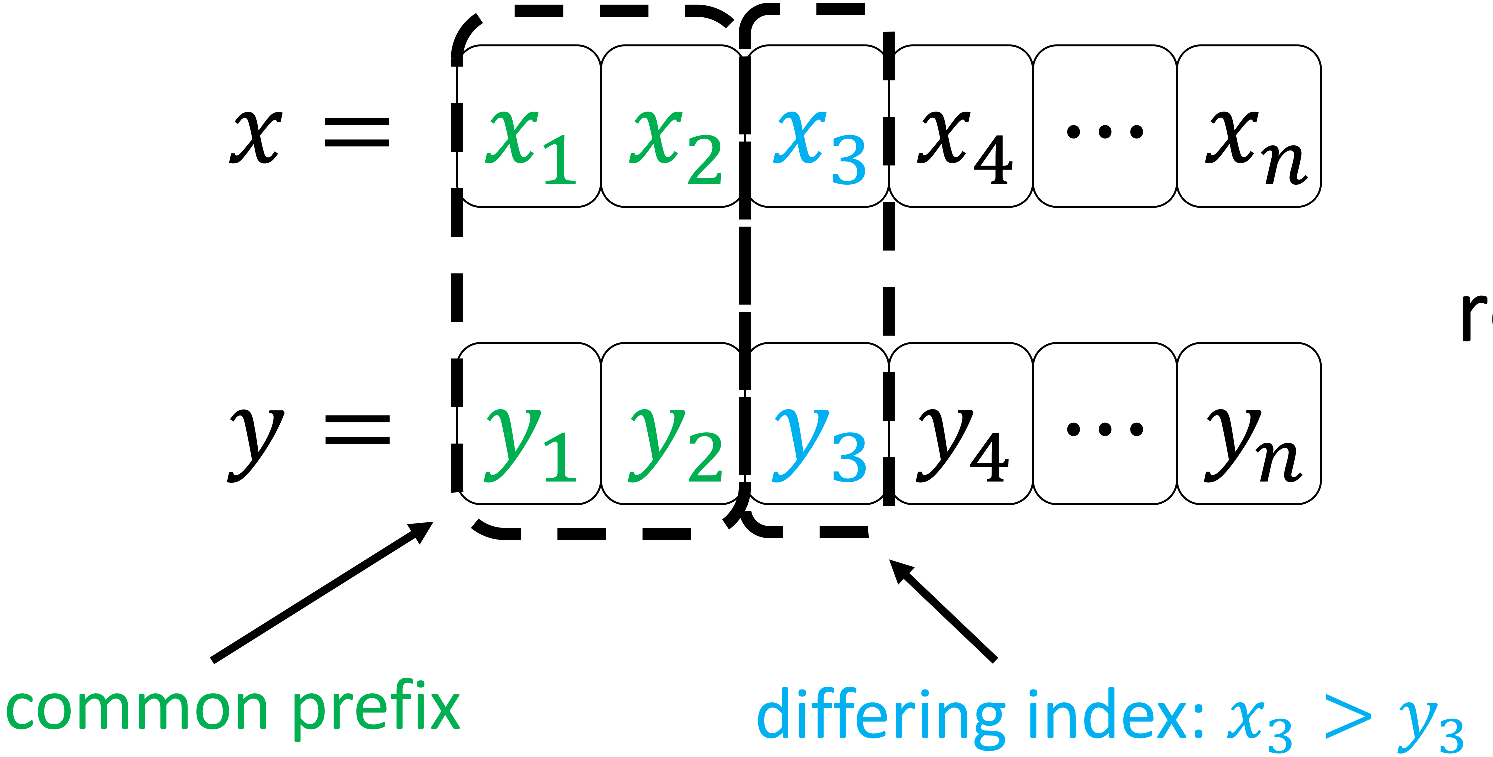
$$x = \boxed{x_1}\boxed{x_2}\boxed{x_3}\boxed{x_4}\boxed{\cdots}\boxed{x_n}$$

$$y = \boxed{y_1}\boxed{y_2}\boxed{y_3}\boxed{y_4}\boxed{\cdots}\boxed{y_n}$$

binary representations

Take two positive integers x, y and consider their binary representations

Comparison Protocol [DGK07, BPTG14]



binary representations

Observation:

$x > y$ if there is an index such that $x_i > y_i$ and for all $j < i$, $x_j = y_j$

Comparison Protocol [DGK07, BPTG14]

$\mathrm{Enc}(x_1) \cdots \mathrm{Enc}(x_n)$

client input: x

server input: y

Step 1: Client sends bitwise encryptions to server

Comparison Protocol [DGK07, BPTG14]

Step 2: Server chooses $s \xleftarrow{\$} \{-1,1\}$ and homomorphically computes

$$\mathrm{Enc}\left(x_i - y_i + s + 3\sum_{j<i}(x_j \oplus y_j)\right)$$

server input: y

Note: encryption scheme needs to be additively homomorphic

Comparison Protocol [DGK07, BPTG14]

Term server computes:

$$w_i := \boxed{x_i - y_i + s} + \boxed{3\sum_{j<i}(x_j \oplus y_j)}$$

If $s = 1$, $x_i - y_i + s = 0$ if and only if $x_i < y_i$

If $s = -1$, $x_i - y_i + s = 0$ if and only if $x_i > y_i$

Always non-negative, and if non-zero, then $w_i > 0$

Comparison Protocol [DGK07, BPTG14]

Term server computes:

$$w_i := \boxed{x_i - y_i + s} + \boxed{3 \sum_{j<i} (x_j \oplus y_j)}$$

Recall observation:

$x > y$ if and only if there is i such that $x_i > y_i$ and for all $j < i$, $x_j = y_j$

if $s = -1$, $x > y$ if and only if there exists i such that $w_i = 0$
if $s = 1$, $x < y$ if and only if there exists i such that $w_i = 0$

Comparison Protocol [DGK07, BPTG14]

$\mathrm{Enc}(w_1) \cdots \mathrm{Enc}(w_n)$

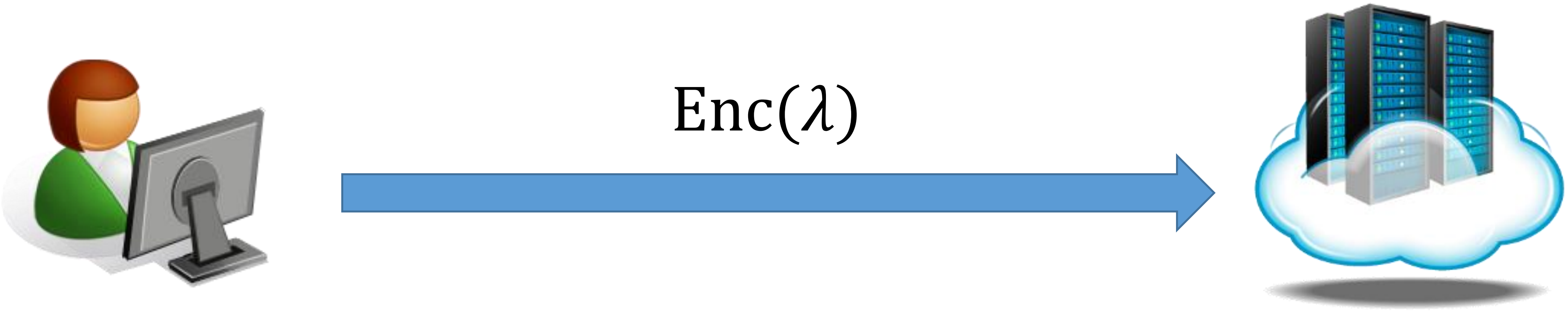
client input: x

server input: y

Step 3: Server sends back $\mathrm{Enc}(w_1) \cdots \mathrm{Enc}(w_n)$

Technical detail: Server first multiplies by a random non-zero element

Comparison Protocol [DGK07, BPTG14]



client input: x

server input: y

Step 4: Client decrypts the w_i and sends back $\mathrm{Enc}(\lambda)$ where $\lambda = 1$ only if there exists i such that $w_i = 0$ and 0 otherwise

Comparison Protocol [DGK07, BPTG14]

Step 5: Given $\mathrm{Enc}(\lambda)$ and s, server can compute result of comparison:

$$\mathrm{Enc}(\mathbf{1}\{x < y\}).$$

server input: y

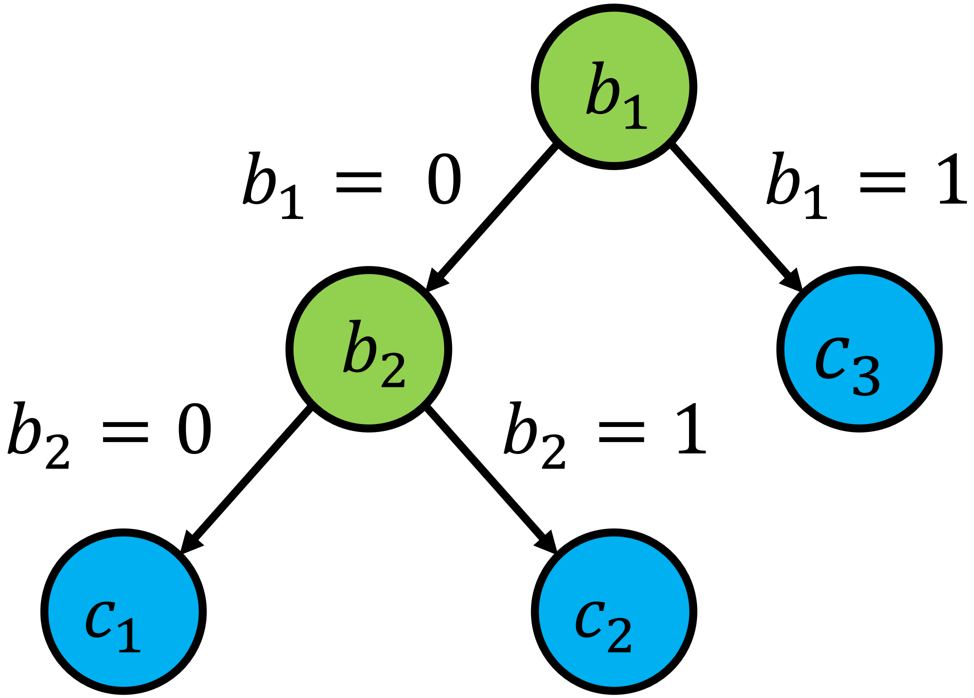
Recall:

if $s = -1$, $x > y$ if and only if there exists i such that $w_i = 0$

if $s = 1$, $x < y$ if and only if there exists i such that $w_i = 0$

Semi-honest Secure Protocol

Key Idea: suppose we give the client b_1, b_2, and the structure of the tree



Then, client can compute the *index* of the outcome

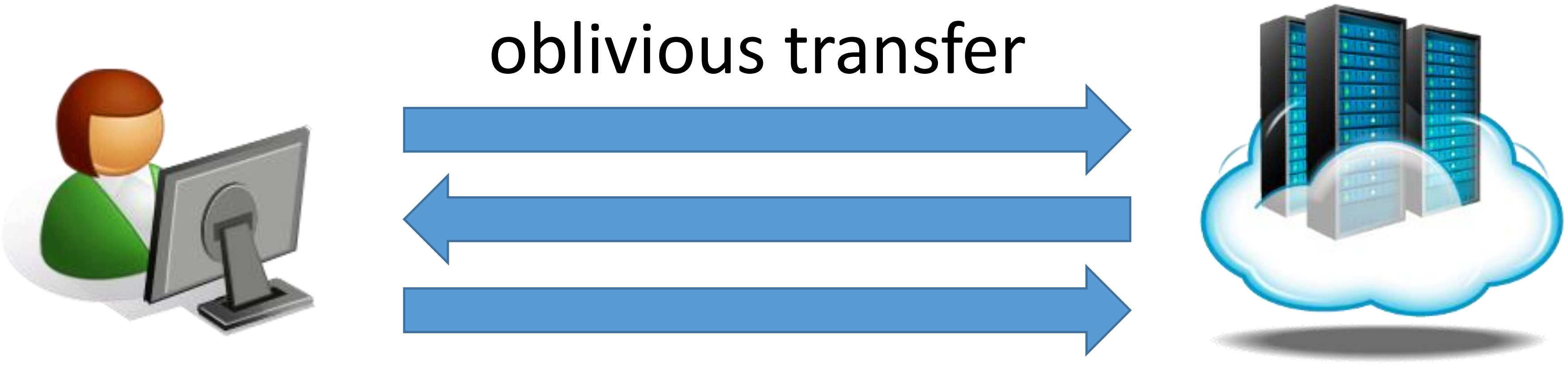
Problem: Leaks the structure of the tree!

Semi-honest Secure Protocol

Suppose client knew the index of the outcome

Problem reduces to well-studied problem: oblivious transfer

Oblivious Transfer (OT)



client's input:
index i

server's input:
database $\{m_1, \ldots, m_n\}$

Desired functionality:

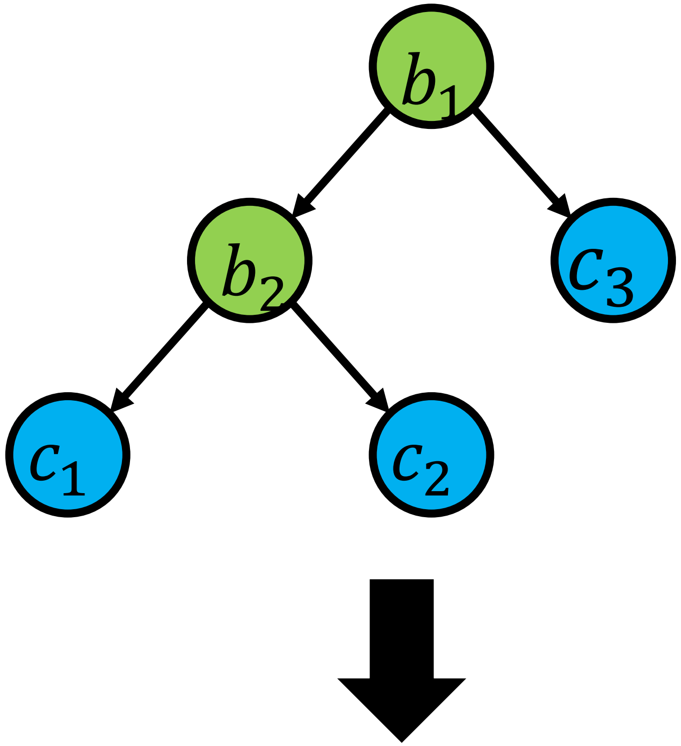
Client learns m_i and nothing else, server learns nothing

Semi-honest Secure Protocol

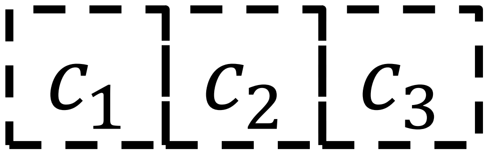
Suppose client knew the index of the outcome

Problem reduces to OT: treat leaves as database, client knows index

Problem: Need to hide structure!

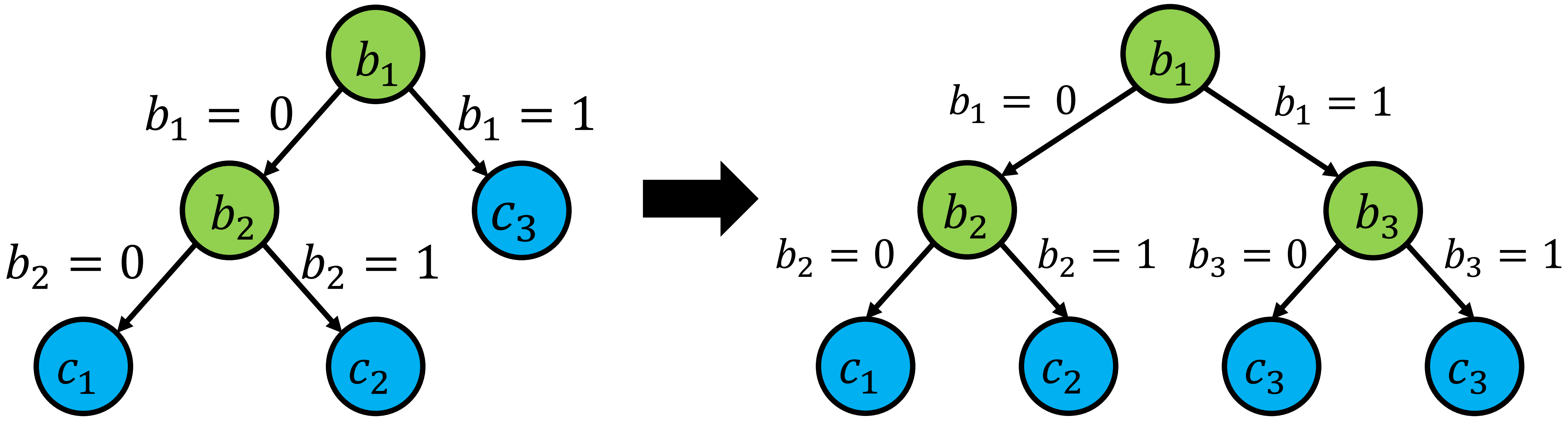


leaves become OT database



Hiding the Structure

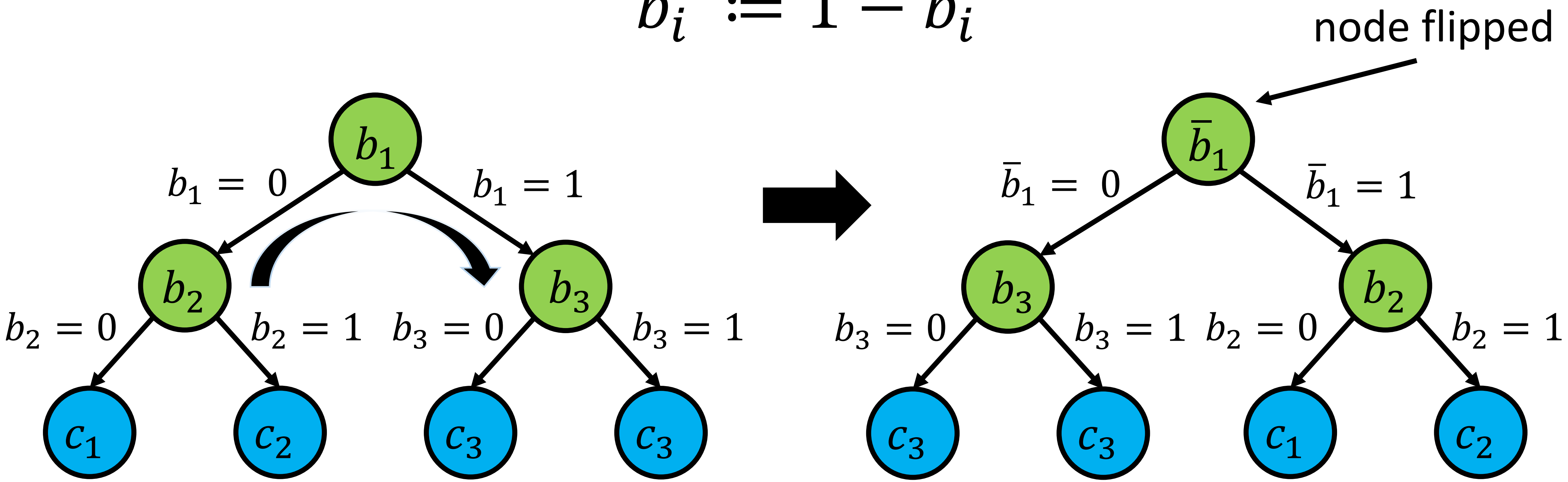
1. Padding: Insert “dummy” nodes to obtain complete tree



Hiding the Structure

2. Randomization: Randomly flip decision variables:

$$\bar{b}_i := 1 - b_i$$



Hiding the Structure: Randomization

Choose

$$s = s_1 s_2 \dots s_m \leftarrow \{0,1\}^m$$

uniformly at random

If $s_i = 1$ then flip

$$b_i \mapsto 1 - b_i$$

Semi-honest Secure Protocol

1. **Server:** Pad and randomize the decision tree
2. **Server & Client:** Engage in comparison protocol to compute each b_i
3. **Client:** Compute the index j of the leaf node
4. **Client & Server:** Engage in OT to obtain c_j

Theorem. This protocol is secure against *semi-honest* adversaries.

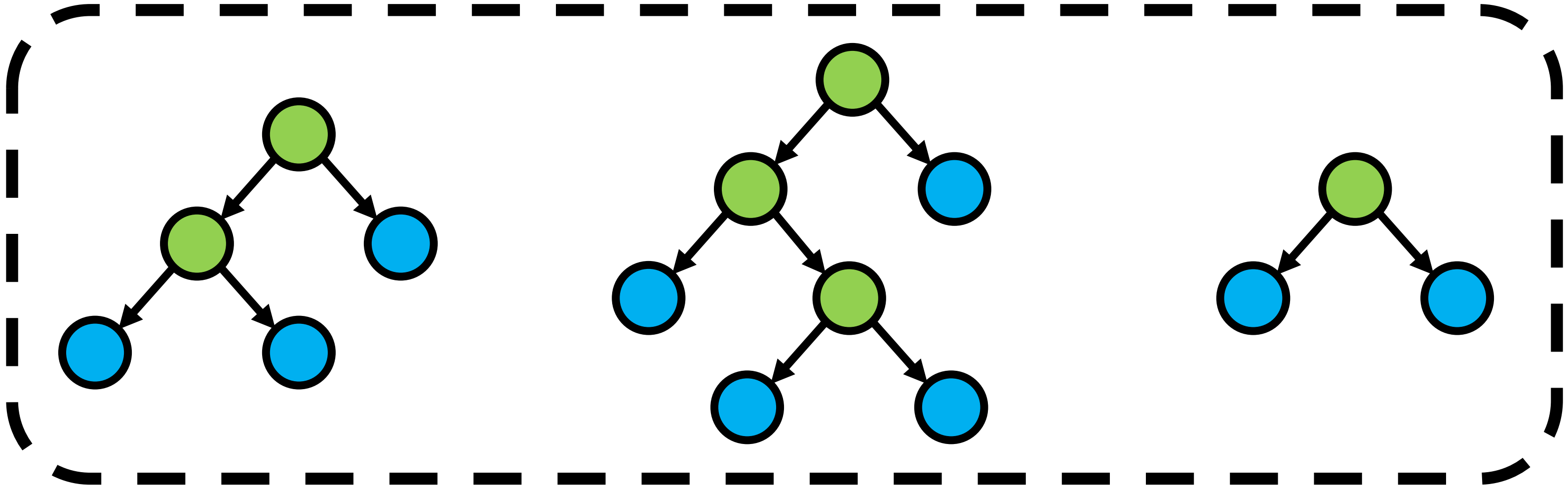
From Trees to Forests

Naïve Solution: Evaluate each tree independently using the protocol

Problem: Reveals more information about the model than just the classification

From Trees to Forests

Better Solution: Use an additive secret-sharing to hide intermediate results



Evaluate each tree as before, but each individual evaluation now looks random

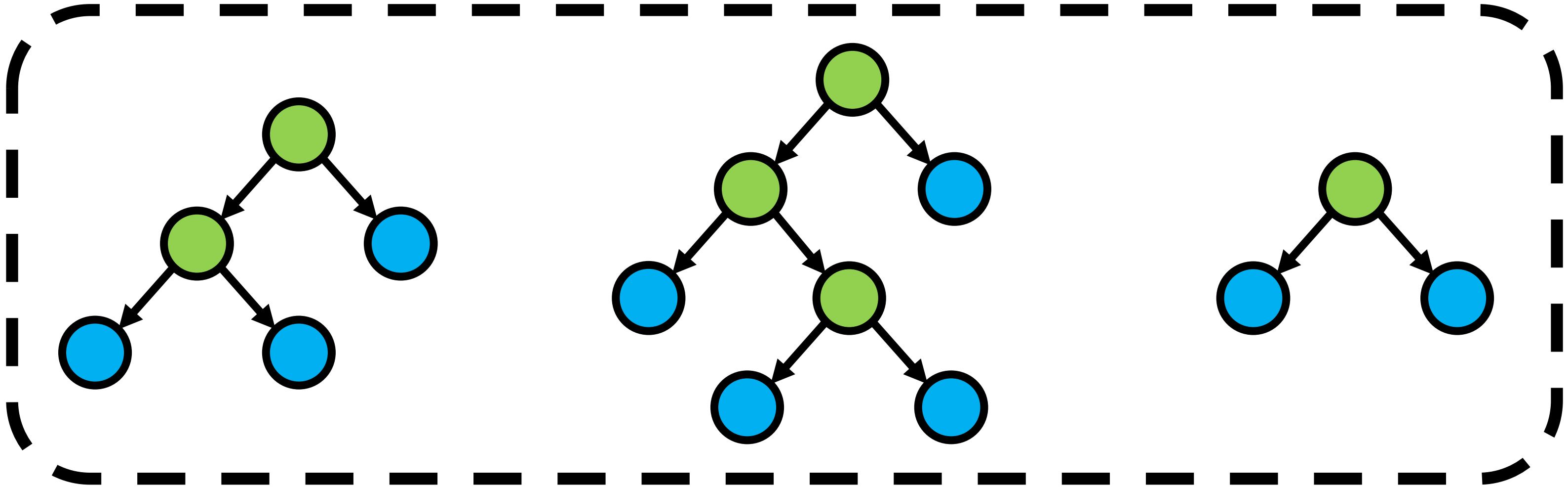
add r_1 to each classification

add r_2 to each classification

add r_3 to each classification

From Trees to Forests

Better Solution: Use an additive secret-sharing to hide intermediate results



add r_1 to each classification

add r_2 to each classification

add r_3 to each classification

Reveal $\sum_i r_i$ to the client, which allows client to learn sum (mean) of predicted values

Implementation

Implementation

Implemented private decision tree + random forest protocol (semi-honest security)

Two primary components:

- Comparison protocol
- Oblivious Transfer

Implementation

Comparison protocol instantiated with exponential variant of ElGamal encryption

- Fast instantiation using elliptic curves

Oblivious transfer based on Naor-Pinkas with OT Extensions

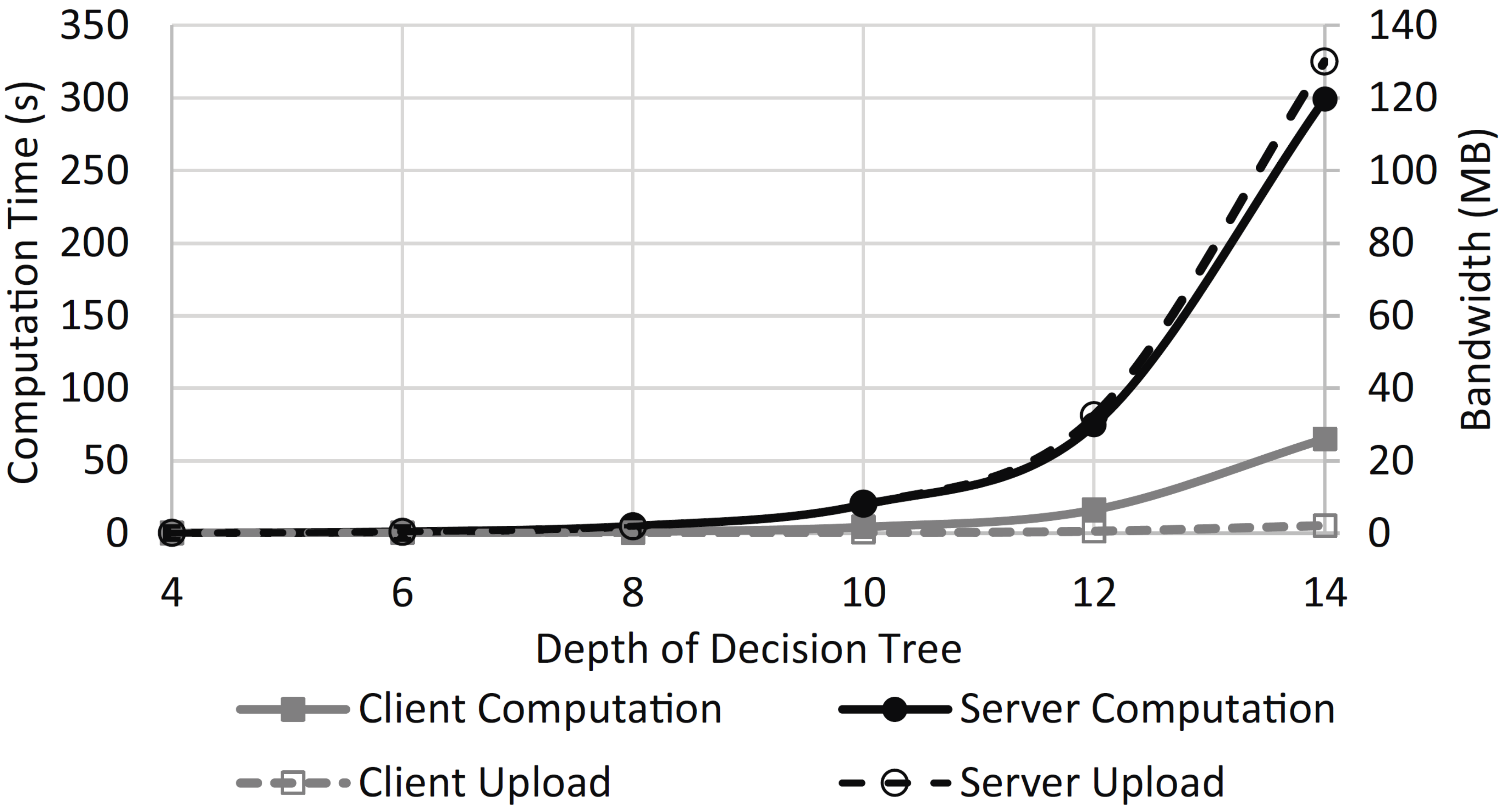
Decision Tree Evaluation on ECG Data

	Security Level	Computation (s)		Bandwidth (KB)
		Client	Server	
[BFK+09]	80	1.765	4.235	112.2
[BPGT14]	80	1.485	2.595	4272
This work	**128**	**0.091**	**0.188**	**101.9**

Experimental Parameters:

- Data Dimension: 6
- Depth of Decision Tree: 4
- Number of Comparisons: 6

Performance for Complete Decision Trees



One-Sided Security (Malicious Model)

Privacy of the server's model is ensured against a malicious client

Privacy of the client's input is ensured against a malicious server

However, client not guaranteed to receive "correct" answer

Extensions to One-Sided Security

Possible attacks on semi-honest protocol:

1. **Server:** Pad and randomize the decision tree
2. **Server & Client:** Engage in comparison protocol to compute each b_i
3. **Client:** Compute the index j of the leaf node containing the response
4. **Client & Server:** Engage in OT to obtain c_j

Client might cheat during comparison protocol (for example, encrypt a value that is not 0/1)

Solution: zero-knowledge proofs

Client might cheat by requesting a different index

Solution: “conditional” oblivious transfer

Conclusion

Simple protocols for decision tree evaluation in both semi-honest and malicious setting

Semi-honest decision tree / random forest evaluation protocols are fairly practical