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The IPS Compiler and Related Constructions

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Technion

Back to the 1980s

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- Zero-knowledge proofs for NP [GMR85,GMW86]
- Computational MPC with no honest majority [Yao86, GMW87]
- Unconditional MPC with honest majority [BGW88, CCD88, RB89]
- Unconditional MPC with no honest majority assuming ideal OT [Kilian88]

- Are these unrelated?

Message of this talk

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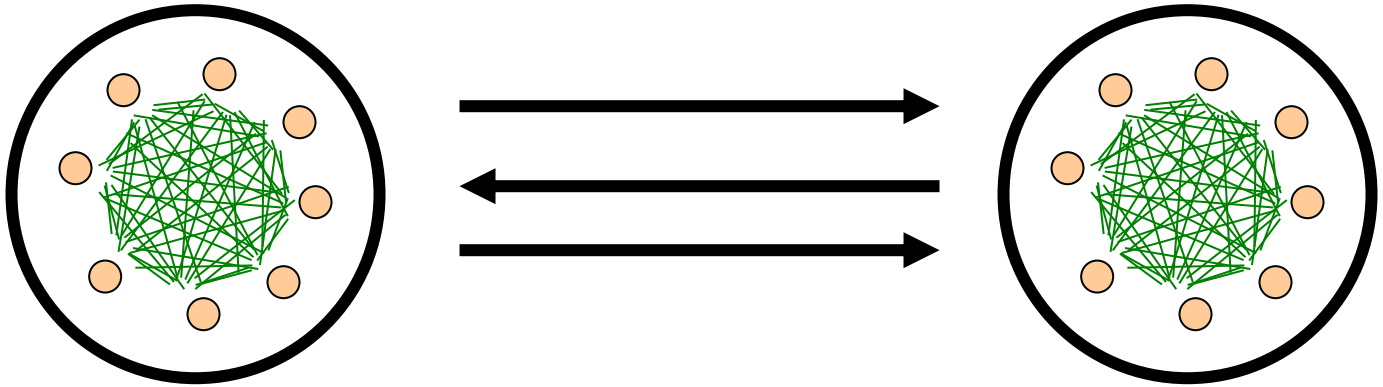
- Honest-majority MPC is useful even when there is no honest majority



- Establishes unexpected relations between classical results
- New results for MPC with no honest majority

Allison

Research interests:
- zero-knowledge proofs
- efficient two-party protocols

Bernard

Research interests:
- information-theoretic cryptography
- honest-majority MPC

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some relevance

no relevance?

Allison

Bernard

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Research interests:

- zero-knowledge proofs
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Research interests:

- information-theoretic cryptography
- honest-majority MPC

Want to hear about my latest and coolest VSS protocol?

what a dork…

Helping make the match

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- **Add to Allison's world a simple ideal functionality**
  - Ideal commitment oracle for ZK (Com-hybrid model)
  - Ideal OT oracle for general protocols (OT-hybrid model)
- **Makes unconditional (and UC) security possible**
  - Analogous to secure channels in Bernard's world
- **Why should Allison be happy?**
  - Generality: Com or OT can be realized in a variety of models, under a variety of assumptions
  - Efficiency: Com or OT can be realized with little overhead
    - Essentially free given preprocessing [BG89]
    - Cheap preprocessing: fast OT [...,PVW08], faster OT extension [Bea96,IKNP03,...]
- **Still: Why should Bernard's research be relevant?**

Helping make the match

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- **Add to Allison's world a simple ideal functionality**
  - Ideal com[illegible]–hybrid model)
  - Ideal C[illegible]rid model)
- **Makes[illegible]ssible**
  - A[illegible]
- **Wh[illegible]**
  - G[illegible]iety of m[illegible]
  - Efficienc[illegible]h little overhead
    - Essentially free given p[illegible]g [BG89]
    - Cheap prepro[illegible]ng: fast OT [...,PVW08], faster OT exte[illegible]on [Bea96,IKNP03,...]
- **Still: Why should Bernard's research be relevant?**

A high level idea:

- Run MPC "in the head".
- Commit to generated views.
- Use consistency checks to ensure honest majority.

Zero-knowledge proofs

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- **Goal: ZK proof for an NP-relation R(x,w)**

- **Towards using MPC:**
  - define n-party functionality
    $g(x; w_1,\ldots,w_n) = R(x, w_1 \oplus \ldots \oplus w_n)$
  - use any 2-secure, perfectly correct protocol for g
    - security in semi-honest model
    - honest majority when n>4

MPC → ZK [IKOS07]

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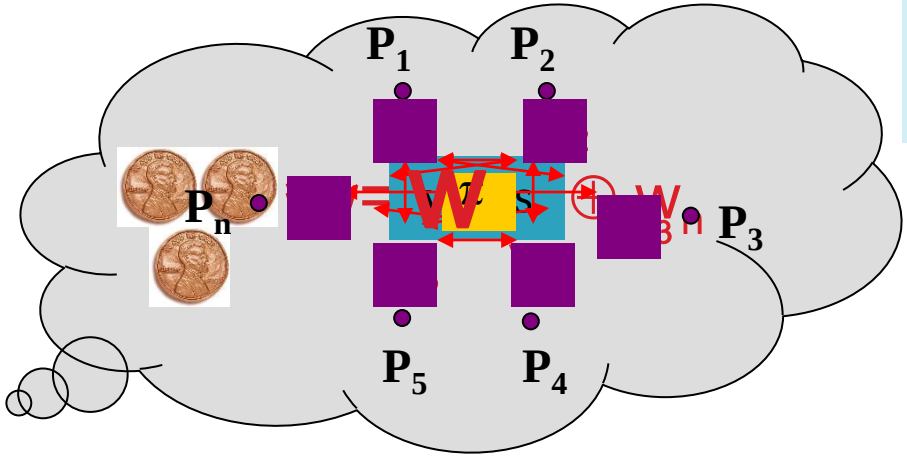
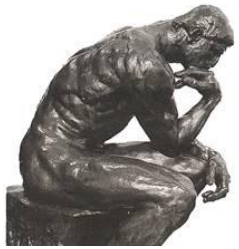


Given MPC protocol π for
$g(x; w_1,...,w_n) = R(x, w_1 \oplus ... \oplus w_n)$

accept iff output=1
&
V_i, V_j are consistent



Prover

Verifier

commit to views $V_1,...,V_n$

random i,j

open views V_i, V_j

Analysis

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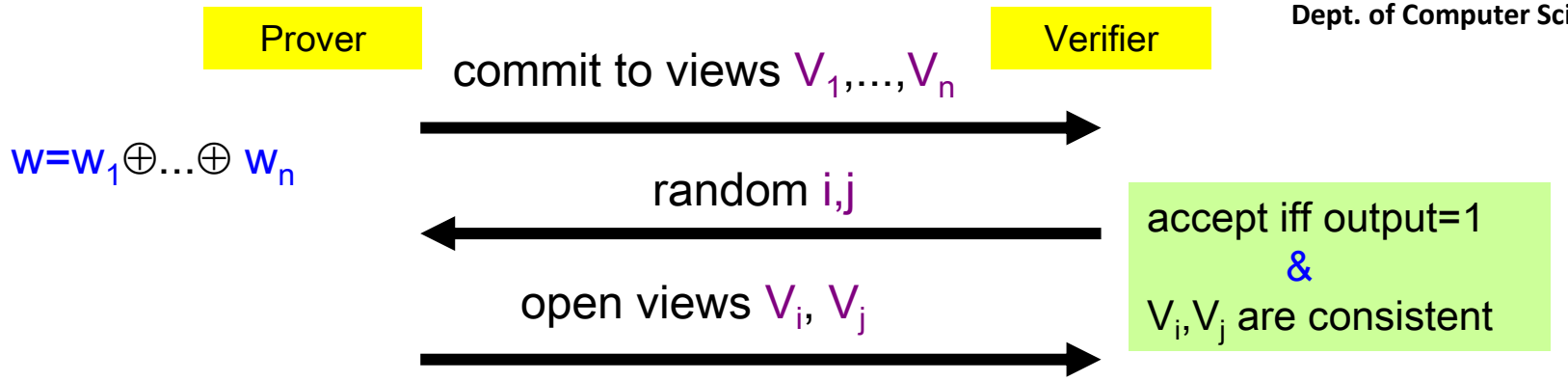

- **Completeness**: √
- **Zero-knowledge**: by 2-security of π and randomness of w_i, w_j.
  (Note: enough to use w_1,w_2,w_3)

Analysis

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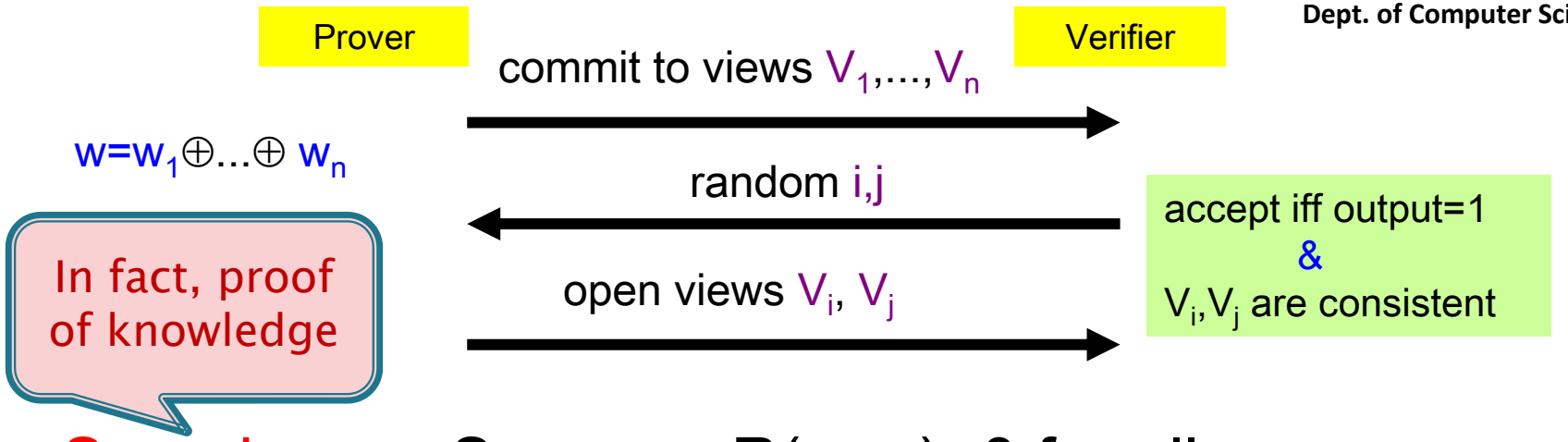

- Soundness: Suppose R(x, w)=0 for all w.

  ➔ either (1) $V_1,\ldots,V_n$ consistent with protocol π

  or (2) $V_1,\ldots,V_n$ not consistent with π

  (1) $\Rightarrow$ outputs=0 (perfect correctness)
  $\Rightarrow$ Verifier rejects

  (2) $\Rightarrow$ for some (i,j), V_i,V_j are inconsistent.
  $\Rightarrow$ Verifier rejects with prob. $\geq 1/n^2$.

Analysis

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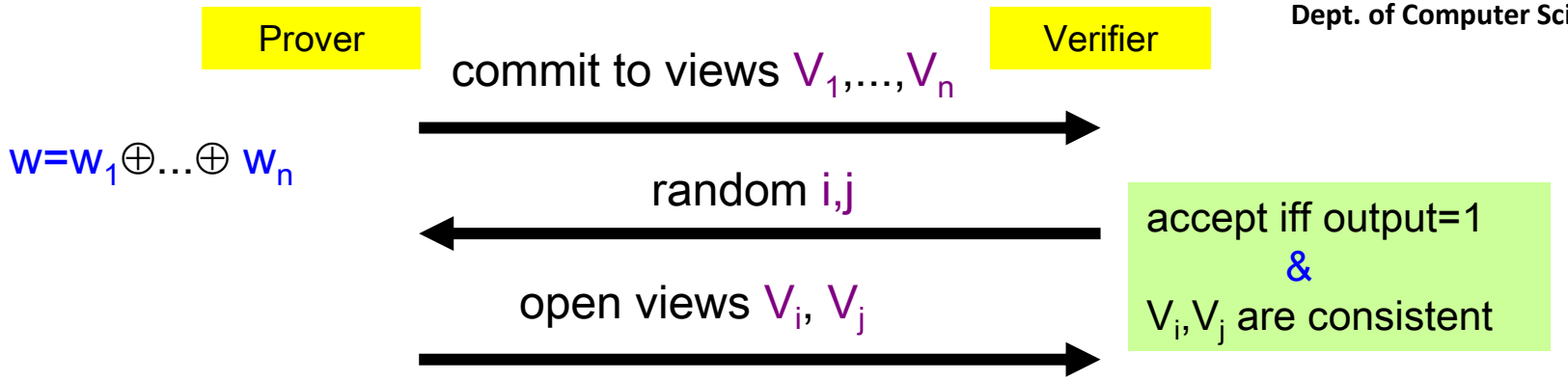

Communication complexity:

$\approx$ (comm. complexity + rand. complexity + input size) of π.

Extensions

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- **Works also with OT-based MPC**
  - Simple consistency check
- **Variant: Use 1-secure MPC**
  - Commit to views of parties + channels
  - Open one view and one incident channel
- **Handle MPC with error via coin-flipping**
- **Variant: Directly get 2^{-k} soundness error via security in malicious model**
  - Two clients, n=O(k) servers
  - $\Omega(n)$-security with abort
  - Broadcast is "free"
- **Realize Com using OWF**

Applications

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- **Simple ZK proofs using:**
  - (1,3) semi-honest MPC [BGW88,CCD88] or [Mau02]
  - (2,3) semi-honest MPC^{OT} [GMW87,GV87,GHY87]
- **ZK with O(|R|)+poly(k) communication**
  - Using protocols from previous talk
  - Asymptotically better alternatives when $|w| \ll |R|$
    - Using FHE
    - Using interactive proofs [GKR08]
    - Efficient arguments [Kil91,Mic94]
- **Many good ZK protocols implied by MPC literature**
  - ZK for linear algebra [CD01,…]

General 2-party protocols [IPS08]

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- **Life is easier when everyone follows instructions…**
- **GMW paradigm** [GMW87]:
  - semi-honest-secure π → malicious-secure π'
  - use ZK proofs to prove "sticking to protocol"
- **Non-black-box: ZK proofs in π' involve code of π**
  - Typically considered "impractical"
  - Not applicable at all when π uses an oracle
    - Functionality oracle: OT-hybrid model
    - Crypto primitive oracle: black-box PRG
    - Arithmetic oracle: black-box field or ring
- **Is there a "black-box alternative" to GMW?**

A dream goal

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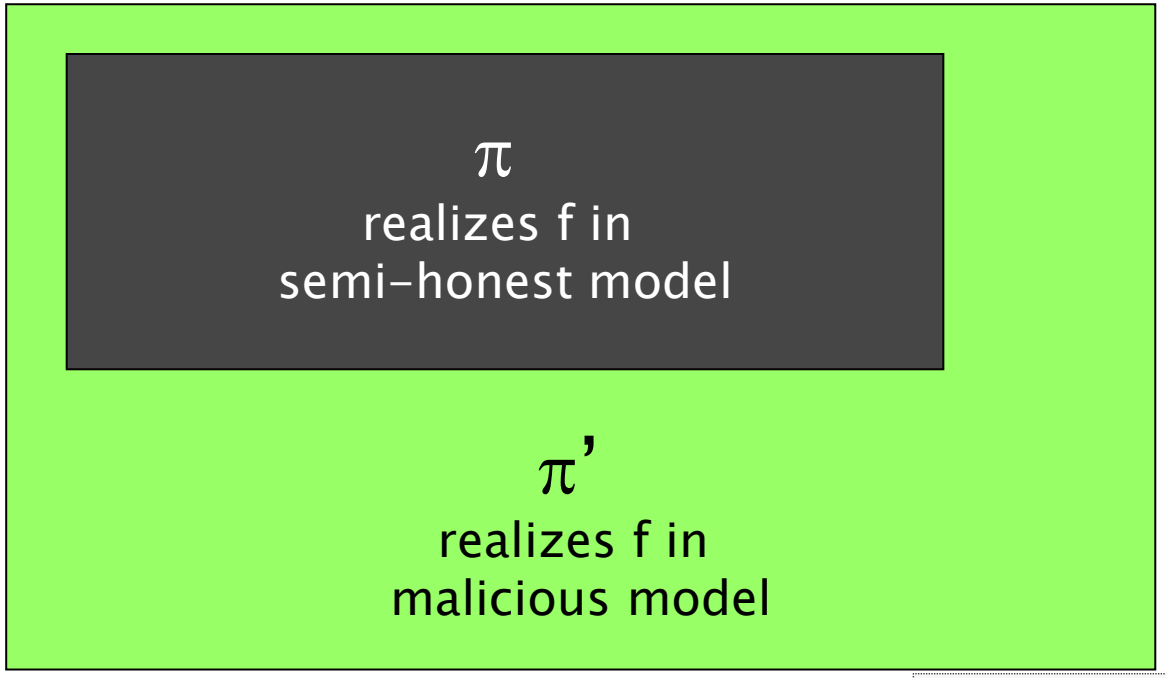

- **Possible for some fixed f**
  - e.g., OT [IKLP06,Hai08]
- **Impossible for general f**
  - e.g., ZK functionalities

Idea

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- **Combine two types of "easy" protocols:**
  - Outer protocol:
    honest-majority MPC
  - Inner protocol:
    semi-honest 2-party protocol
    - possibly in OT-hybrid model

- **Both are easier than our goal**
- **Both exist unconditionally**

Outer protocol

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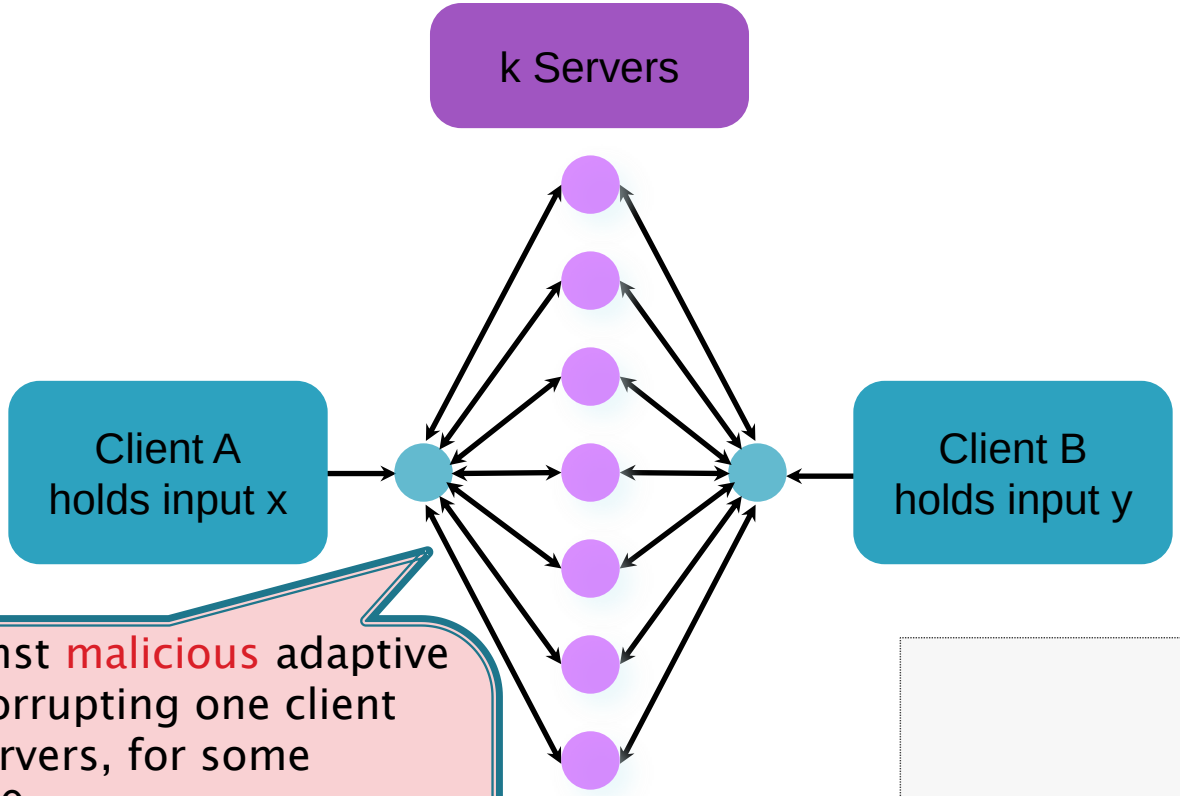

Secure against malicious adaptive adversary corrupting one client and t=ck servers, for some constant c>0.

Security with abort suffices.

Straight-line simulation needed.

Example: "BGW-lite"

Inner protocol

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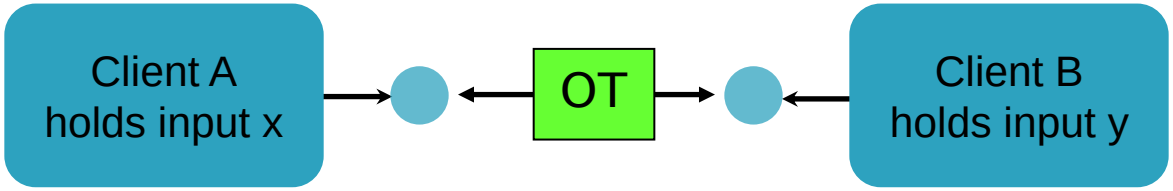

Secure against semi-honest adversary

(Adaptive security w/erasures)

Example: "GMW-lite"

Combining the two protocols

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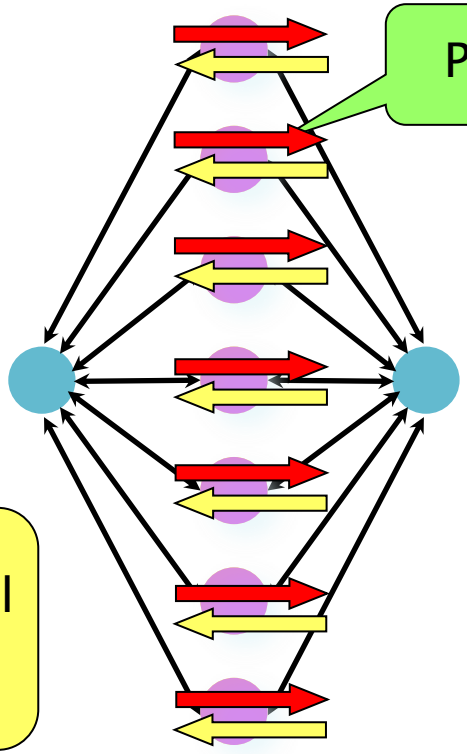
oblivious watch lists



Player virtualization

OT calls by inner protocol are “risky”

outer protocol for f

A closer look at server emulation

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- **Assume server i is deterministic**
  - This is already the case for natural protocols
  - Can be ensured in general with small overhead
- **In outer protocol, server i**
  - gets a message from A and B
  - sends a message to A and B
  - may update a secret state
- **Captured by reactive 2-party functionality F_i**
  - Inputs = incoming messages
  - Outputs = outgoing messages
- **Use semi-honest protocol for F_i**
  - Distribute server between clients
  - "Local" computations do not need to be distributed.

A closer look at watchlists

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- **Inner protocol can't prevent clients from cheating by sending "bad messages"**
  - bad randomness handled via simple coin-tossing
- **Watchlist mechanism ensures that cheating does not occur too often**
  - Client doesn't know which instances of inner protocol are watched
  - Client cheats in $\leq$ t instances
    ➔ cheating tolerated by t-security of outer protocol
  - Client cheats in $>$t instances
    ➔ will be caught with overwhelming probability
- **"Cut-and-choose gone live"**

Setting up the watchlists

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- Each client picks n long one-time pads R_i
- $|R_i|$ = length of messages + randomness in execution of i-th inner protocol
  - Short PRG seed suffices for computational security
- Each client uses OT to select ~ t/2 of the other client's pads R_i
- Implemented via Rabin-OT for each server
  - Reduces to a constant number of (1,2) string-OTs per server for any rational probability p
  - With overwhelming probability, $p \pm 0.01$ fraction of R_i are received

Using the watchlists

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- **Consider here B watching A**
  - A watches B symmetrically
- **A uses sequential parts of each R_i to mask her (progressive) view of the i-th inner protocol**
  - If B obtained R_i, he has full view of i-th inner protocol
  - Can detect (and abort) as soon as A cheats
  - What about ideal OT calls in inner protocol?
    - Cheating caught w/prob ½ if OT inputs are random
    - Use OT to random-OT reduction

Example

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- **Consider outer protocol from previous talk**
- **Each server performs two types of computations:**
  - Send $a_i b_i + z_i$ to A, where a_i is a secret received from A and b_i, z_i are secrets received from B
    - O(|C|) such computations overall
    - Can be implemented by simple inner protocols
      - using homomorphic encryption (e.g., Paillier)
      - unconditionally using OT [GMW87,IPS09]
      - using coding assumptions and OT [NP99,IPS09]
  - Send to A a public linear combination of secrets sent by B (and vice versa)
    - Can be implemented via local computation of B
- **Gives efficient protocols for arithmetic computations**

Simulation (rough idea)

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- **Suppose A is corrupted in final protocol**
- **Main simulator runs outer simulator to**
  - extract input of A
  - generate outer protocol messages from B
  - generate full view of inner protocols watched by A (requires corrupting ~ t/2 servers)
  - generate A's inputs and outputs in other inner protocols (communication of A with servers)
    - feed to inner simulator to generate inner protocol view
    - valid as long as A does not deviate from inner protocol
- **Main simulator can observe deviation from inner protocol**
  - When A cheats on i-th inner protocol, outer simulator corrupts i-th server and main simulator aborts w/prob. p

A new protocol compiler

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- **Given a 2-party functionality F**
  - Get an honest-majority-secure outer protocol Π for the functionality F (with 2 clients and k servers)
  - Get a semi-honest-secure inner protocol ρ^{OT} for a 2-party functionality G^{Π} corresponding to the servers' program in Π

    (G^{Π} is a reactive functionality defined black-box w.r.t Π)

- **Our (2-party) protocol Φ^{OT}, with black-box access to Π and ρ, is a malicious-secure protocol for F.**

A new protocol compiler

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- **Given an m-party functionality F**
  - Get an honest-majority-secure outer protocol Π for the functionality F (with m clients and k servers)
  - Get a semi-honest-secure inner protocol ρ^{OT} for a m-party functionality G^{Π} corresponding to the servers' program in Π

    (G^{Π} is a reactive functionality defined black-box w.r.t Π)

- **Our (m-party) protocol Φ^{OT}, with black-box access to Π and ρ, is a malicious-secure protocol for F.**

Applications

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- **Revisiting the classics**
  - BGW-lite + GMW-lite ➔ Kilian
- **Efficient MPC with no honest majority**
  - O(1) bits per gate in OT-hybrid model (+ additive term)
  - All crypto can be pushed to preprocessing
- **Constant-round MPC^{OT} (t<n) using black-box PRG**
  - Extending 2-party "cut-and-choose" Yao
- **Efficient OT extension**
- **Constant-rate b.b. reduction of OT to semi-honest OT**
- **Constant-rate OT combiners**
- **Secure arithmetic computation over black-box fields/rings**
- **Protocols making black-box use of homomorphic encryption**

Further research I

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- **Find more useful "black-box" connections**
- **Formalized via oracle game:**
  - Protocol move:
    given oracle g, get (arbitrary) protocol oracle π_g
  - Build move:
    given oracle f, build oracle g
  - Goal: given oracle f, obtain a protocol π_f in a "strong" model using only protocol moves in "weaker" model(s)
- **Previous examples**
  - ZK from MPC:
    build – protocol – build
  - New protocol compiler:
    protocol – build – protocol – build

Further research II

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- **Find "leaner" versions of new compiler**
  - Weaker outer protocol?
- **Optimize for practical efficiency?**
  - Many degrees of freedom!