ZKPDL: A Language-Based System for Zero-Knowledge Proofs and Electronic Cash

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Anna Lysyanskaya (Brown University)

Bridging the gap

Crypto

Systems

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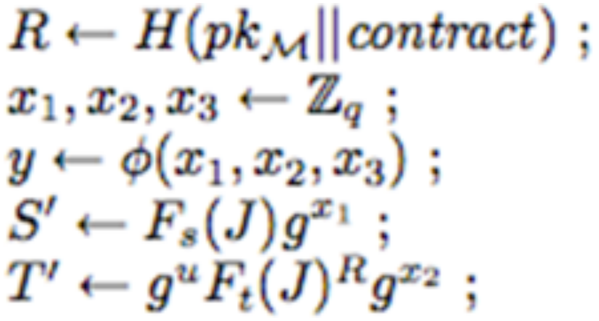
Crypto

Systems



$R \leftarrow H(pk_{\mathcal{M}} || contract)$;

$x_1, x_2, x_3 \leftarrow \mathbb{Z}_q$;

$y \leftarrow \phi(x_1, x_2, x_3)$;

$S' \leftarrow F_s(J) g^{x_1}$;

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Bridging the gap

Crypto

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Systems

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Systems

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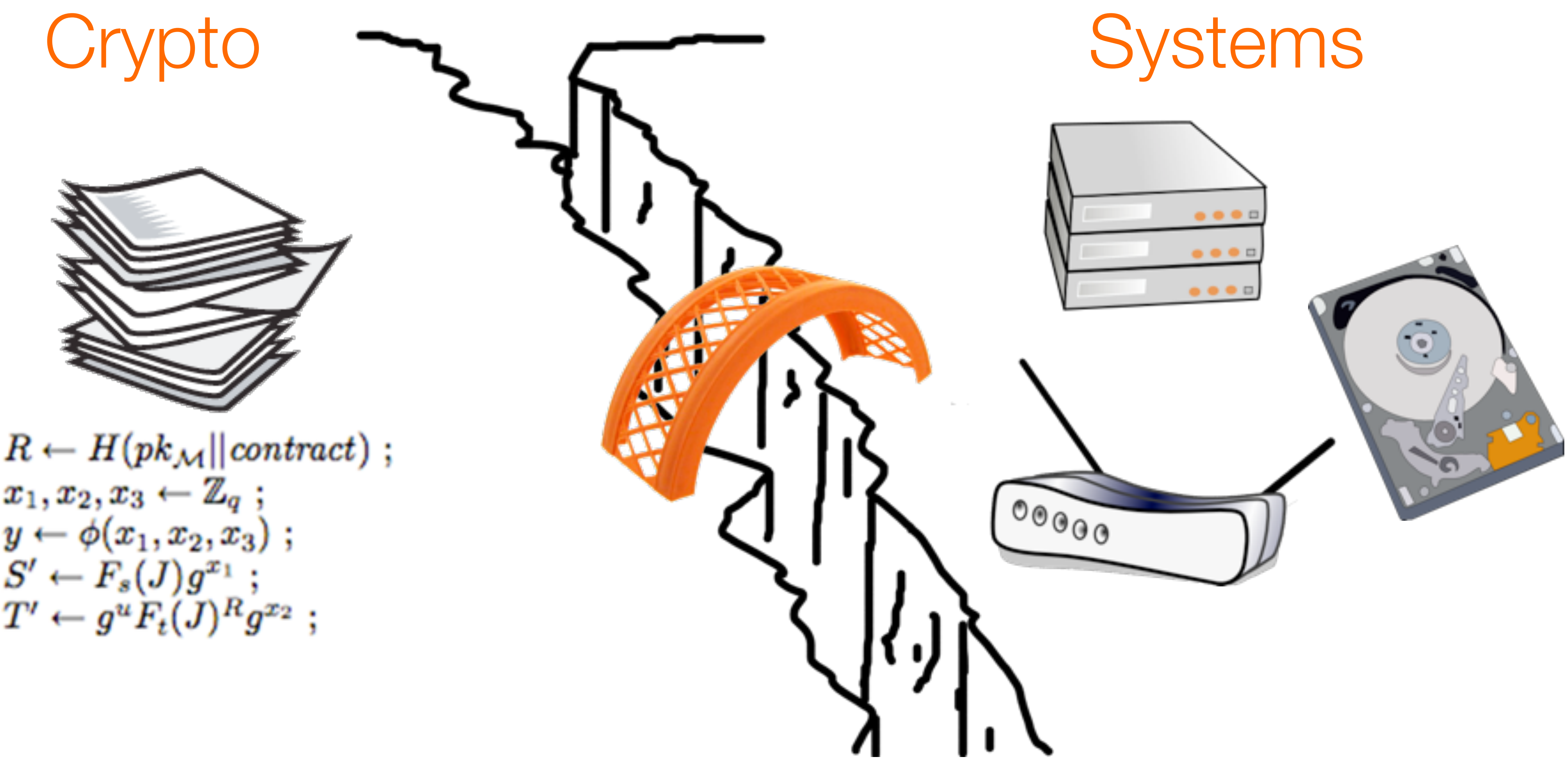

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Systems

Bridging the gap... for zero knowledge proofs

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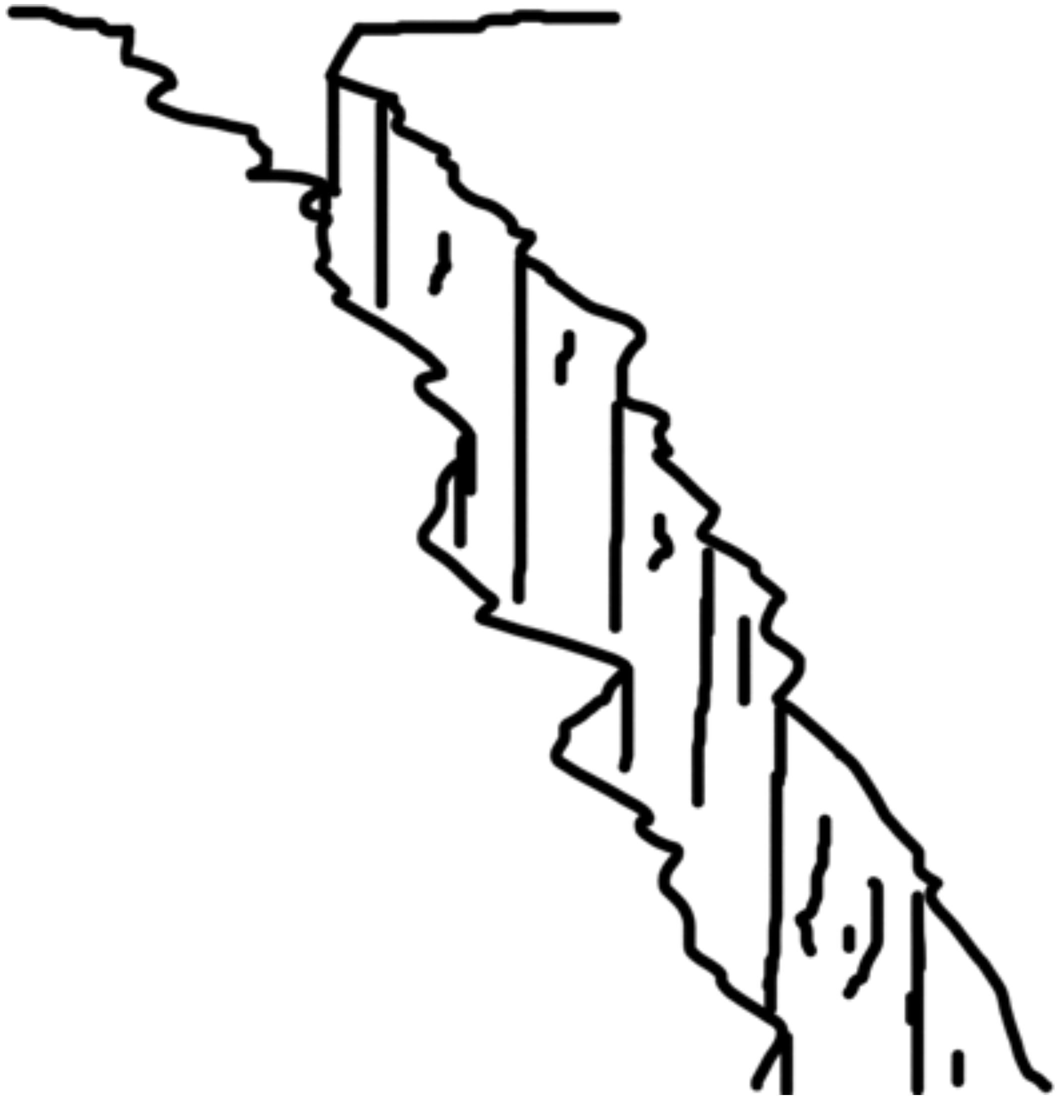

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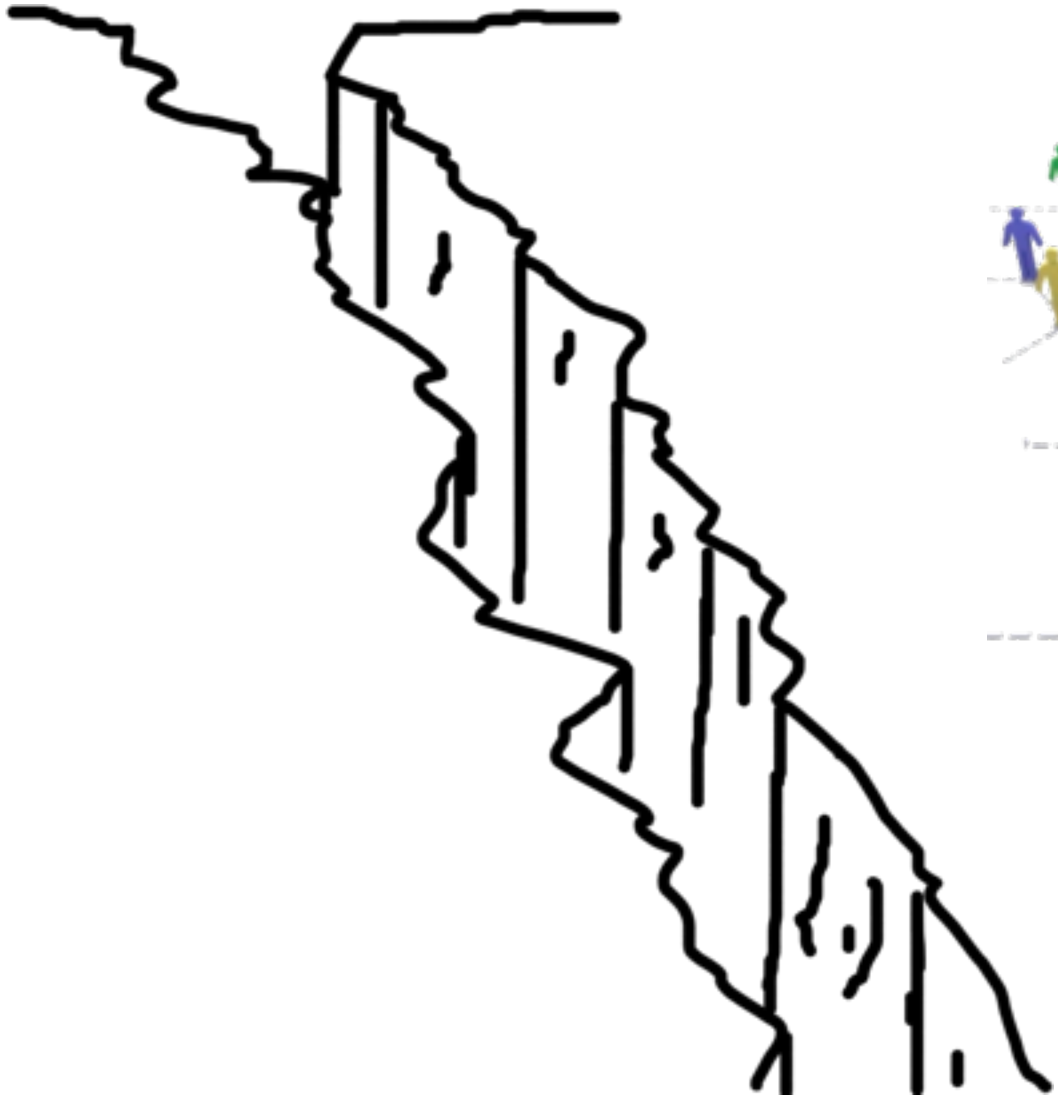


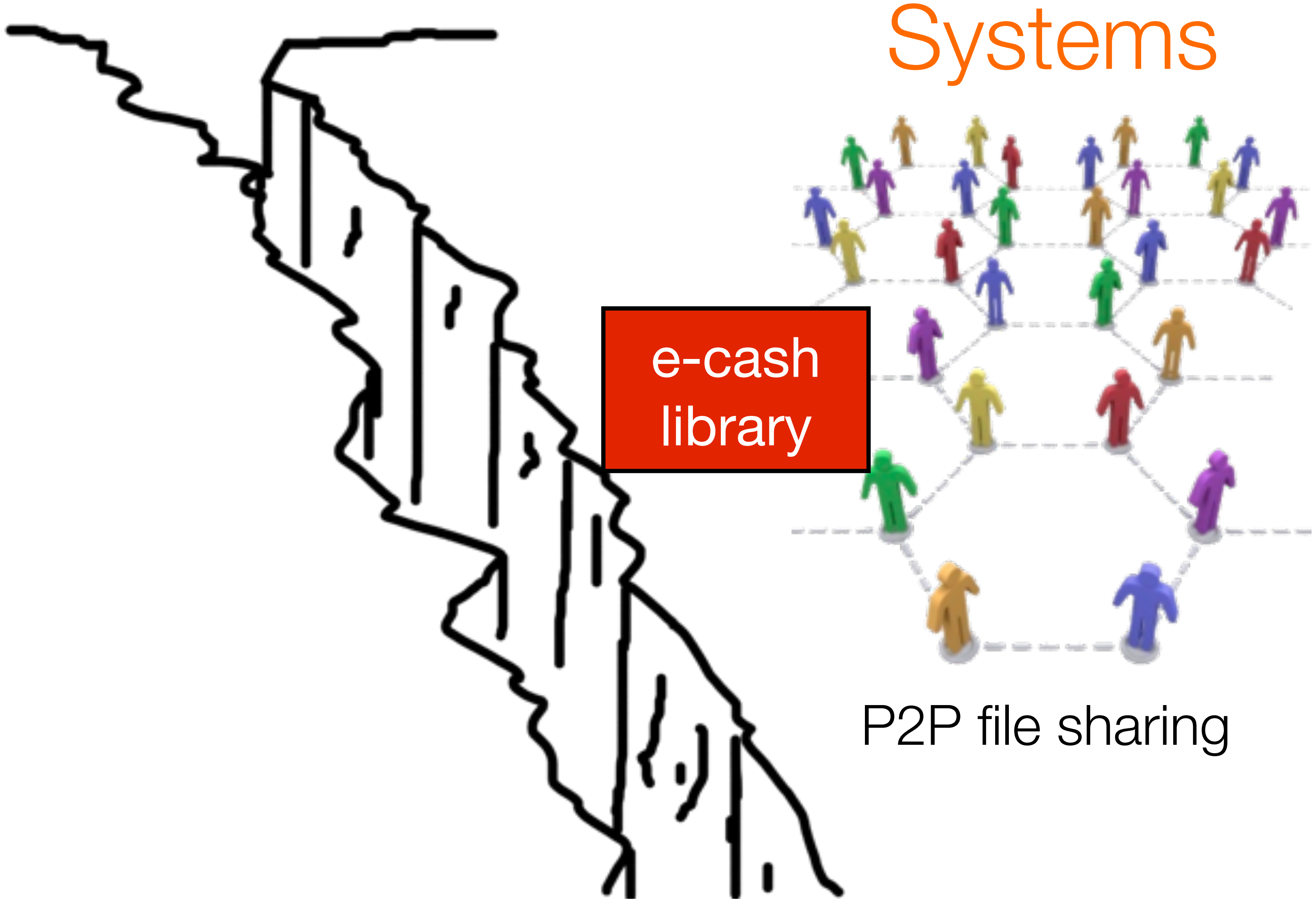
Systems

P2P file sharing

Bridging the gap... for zero knowledge proofs

Crypto

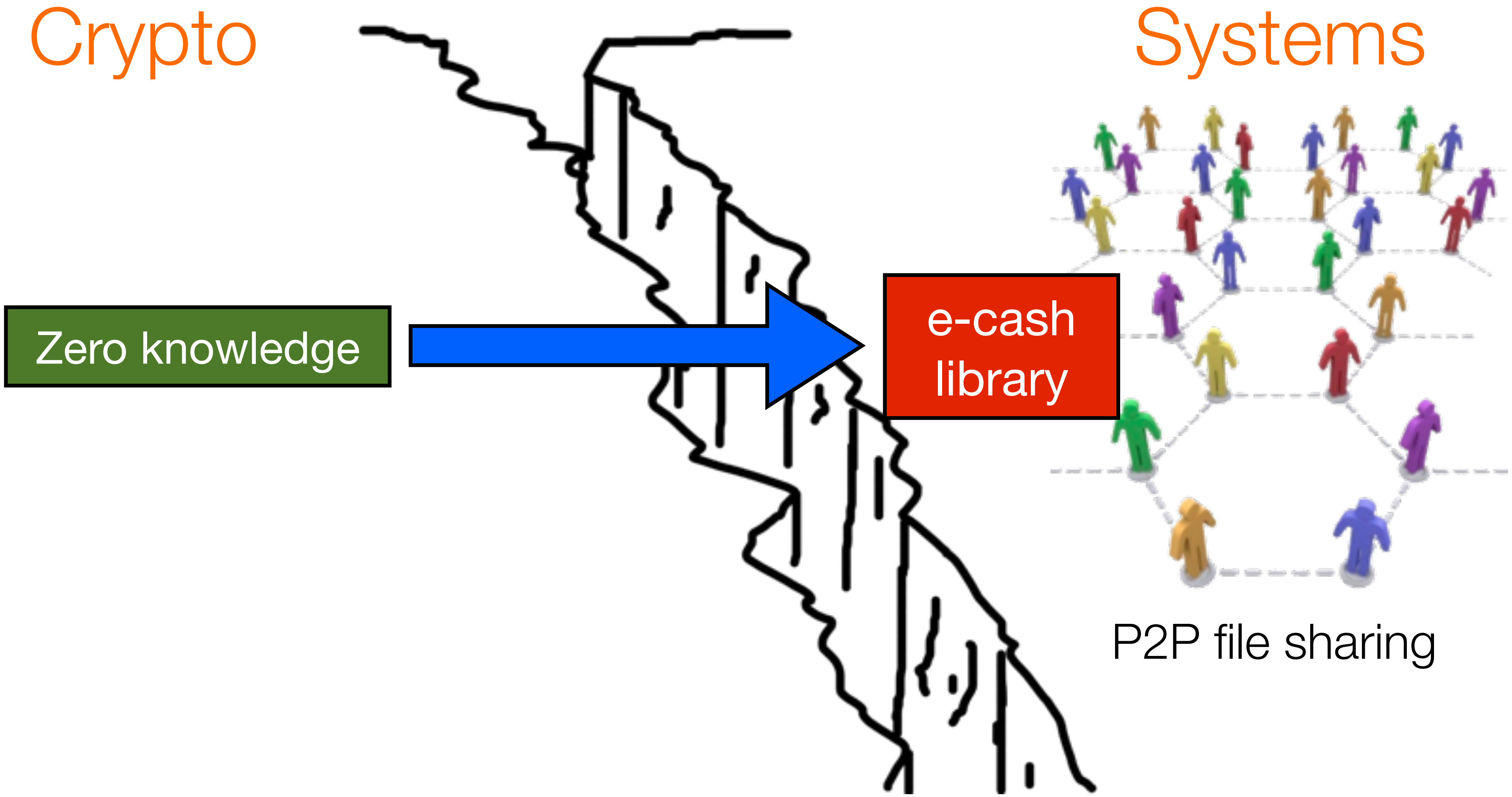
Systems



e-cash library

P2P file sharing

Bridging the gap... for zero knowledge proofs



Crypto

Systems

Zero knowledge

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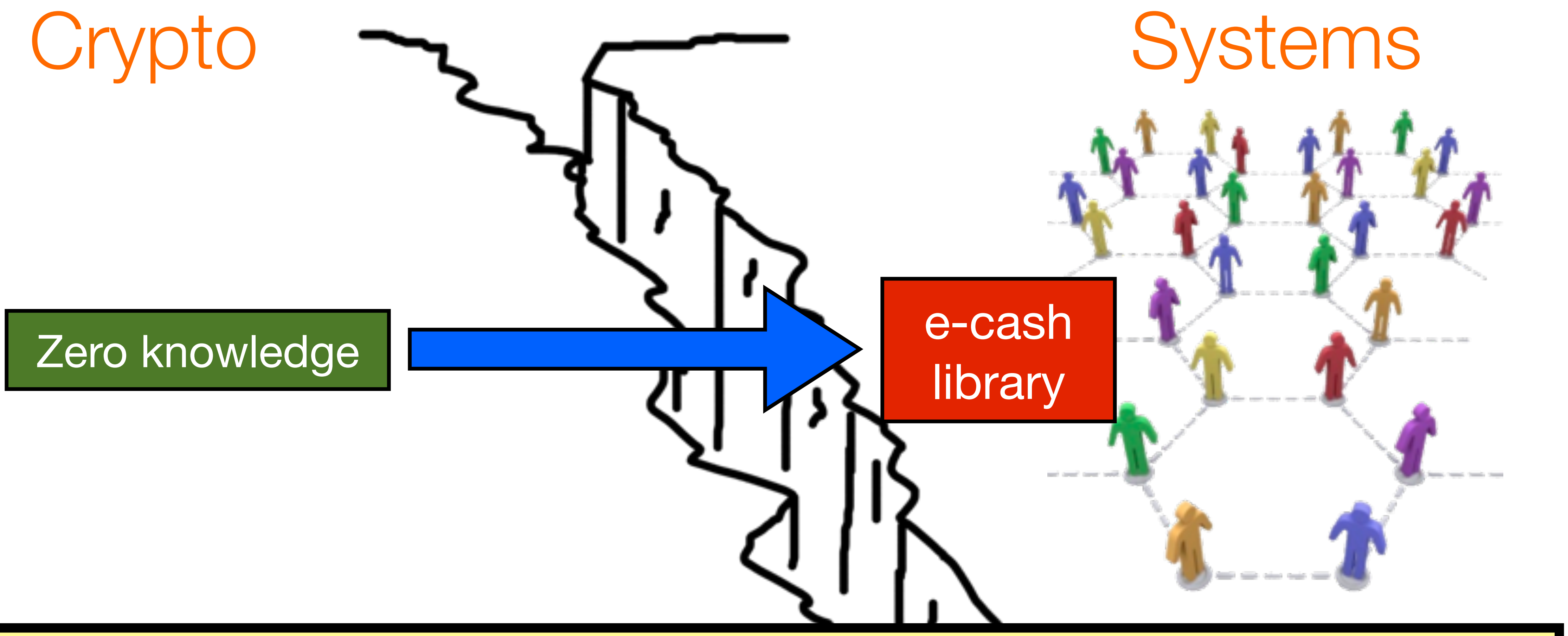

Crypto

Systems

Zero knowledge

e-cash library

Wrote language for zero-knowledge proofs

Removes obstacle, easy to translate from description to implementation

Wrote library for e-cash using this language/interpreter framework

Zero-knowledge proofs [GMR89,BdSMP91]

Prover

Verifier

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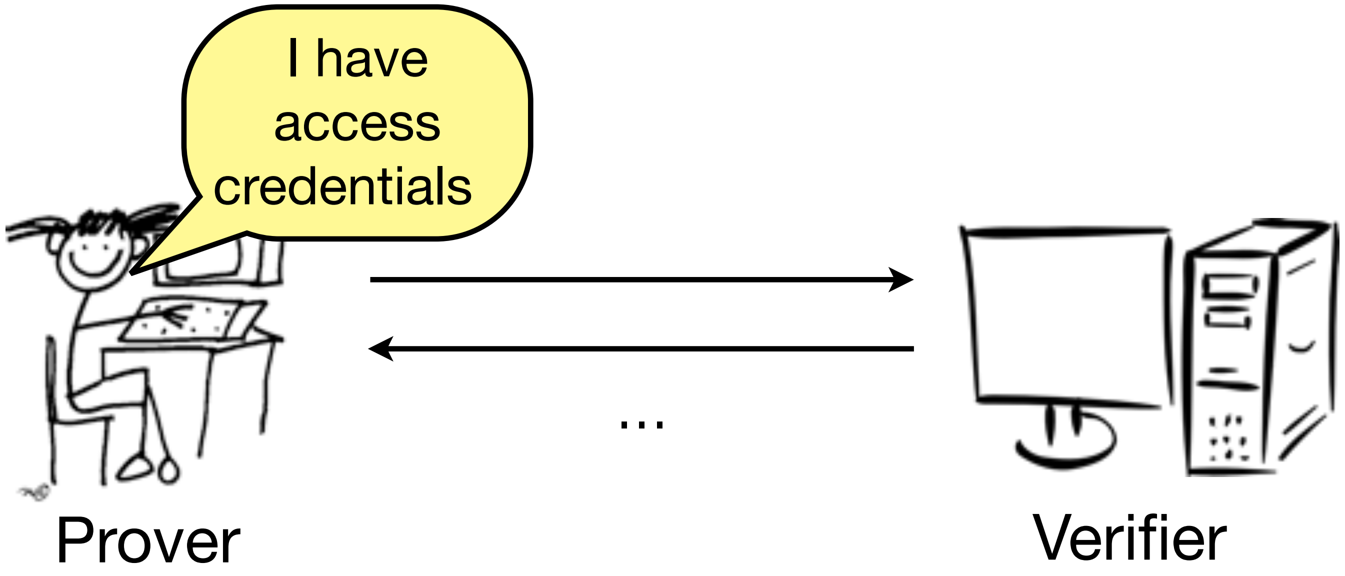
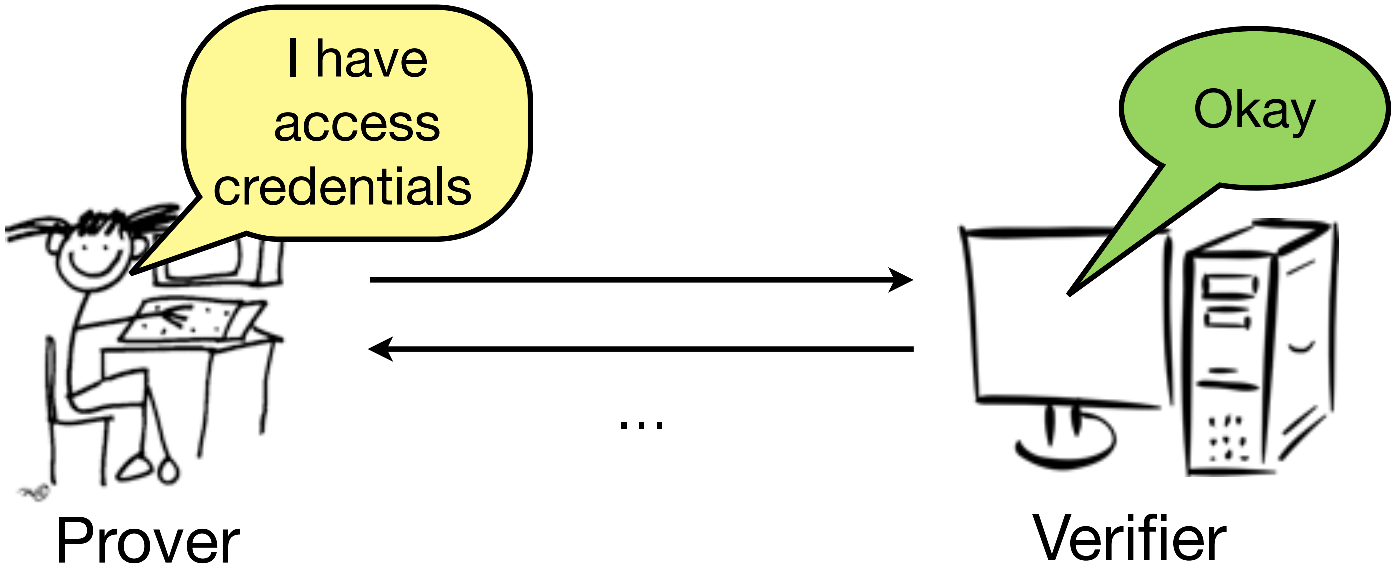
Zero-knowledge proofs [GMR89,BdSMP91]



Zero-knowledge proofs [GMR89,BdSMP91]



I have access credentials

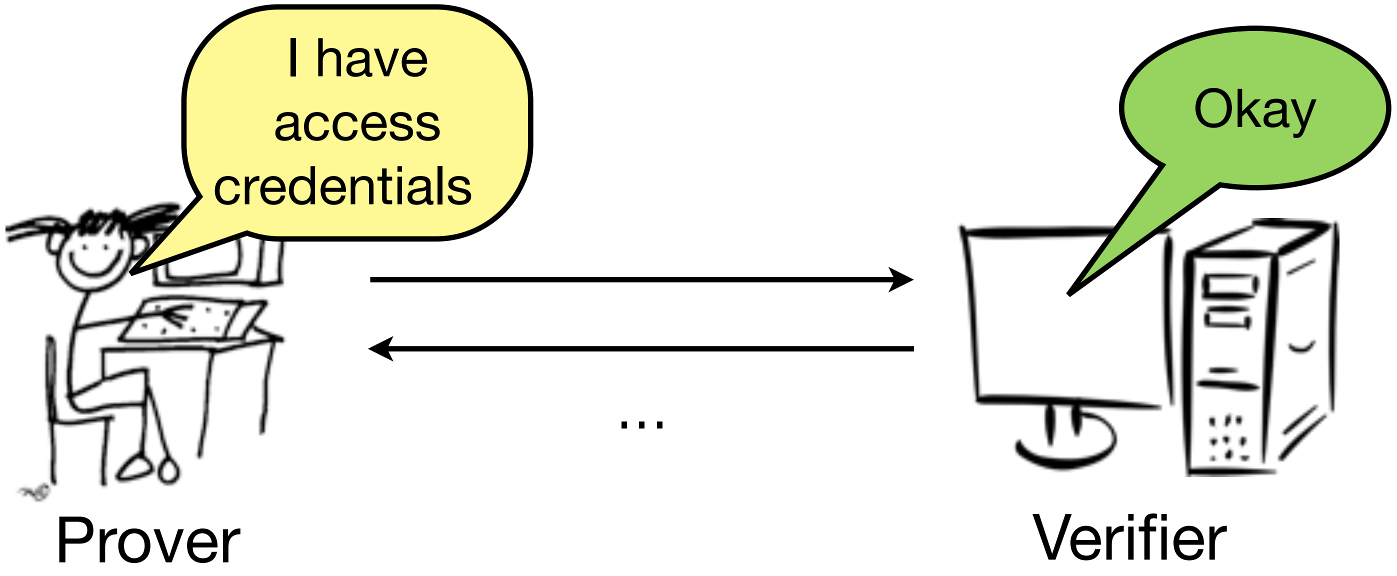
Okay

…

Prover

Verifier

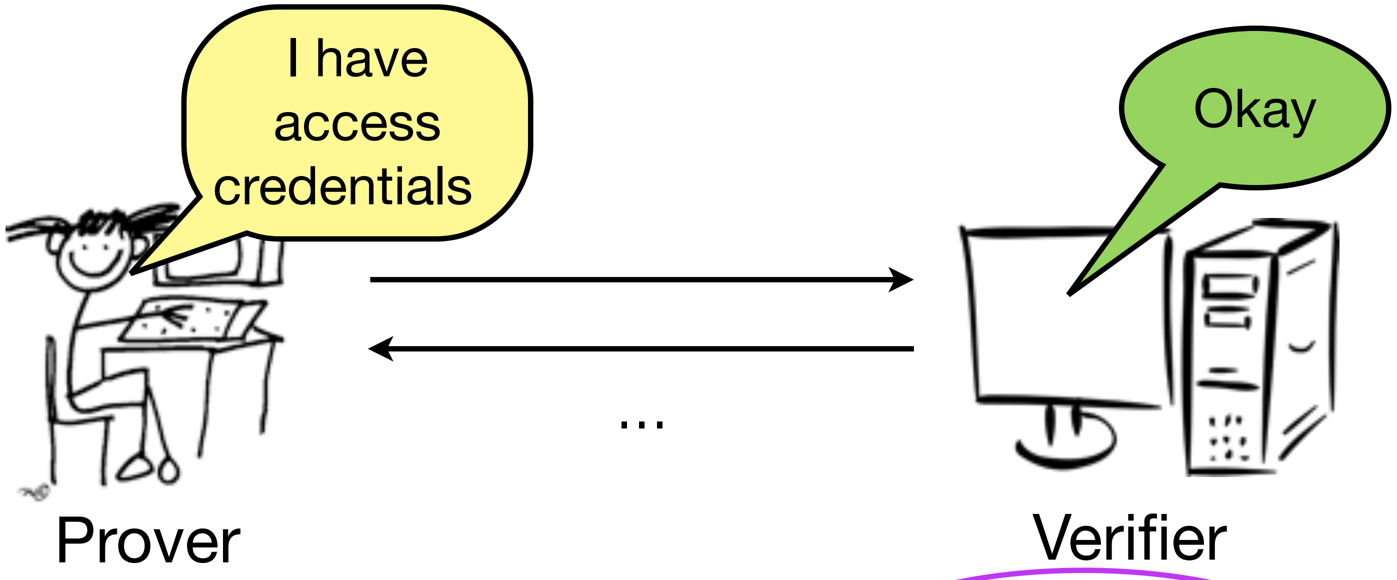
Zero-knowledge proofs [GMR89,BdSMP91]



Soundness: system won’t accept incorrect proof

Zero-knowledge: system won’t learn anything it didn’t already know

Zero-knowledge proofs [GMR89,BdSMP91]

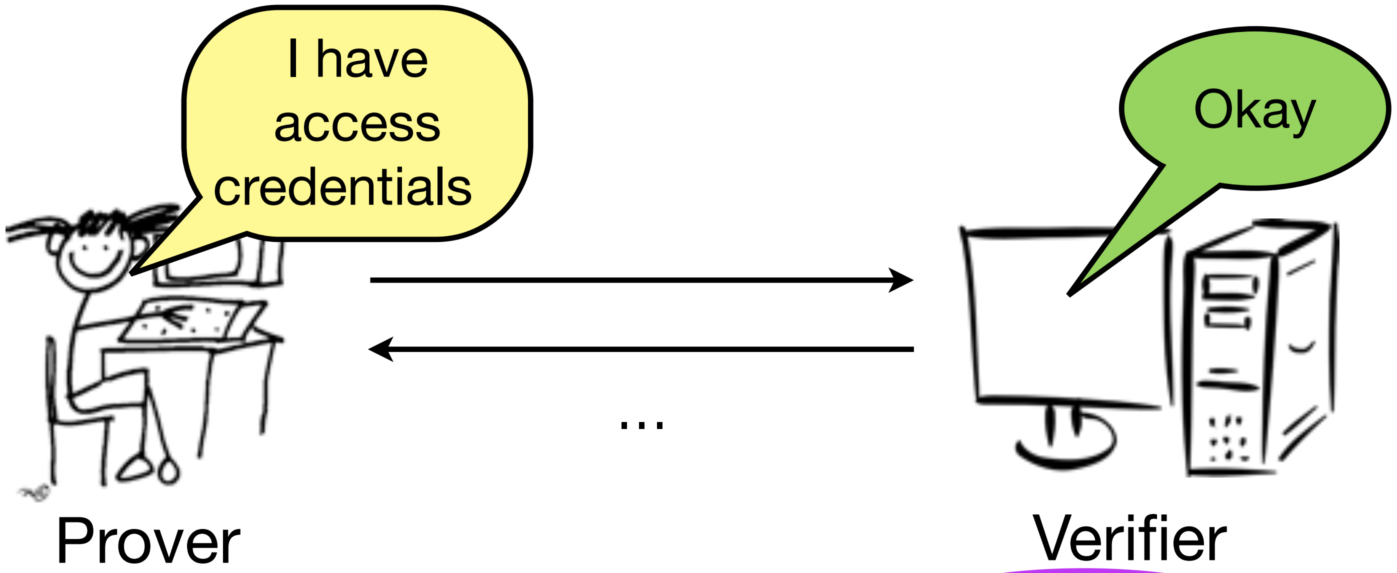


Soundness: system won't accept incorrect proof

Zero-knowledge: system won't learn anything it didn't already know

- fair exchange
- blind signatures
- electronic voting
- anonymous credentials
- multi-party computation
- verifiable encryption
- anonymous onion routing
- non-transferable signatures
- electronic cash
- deniable authentication
- verifiable secret sharing
- group signatures

Zero-knowledge proofs [GMR89,BdSMP91]



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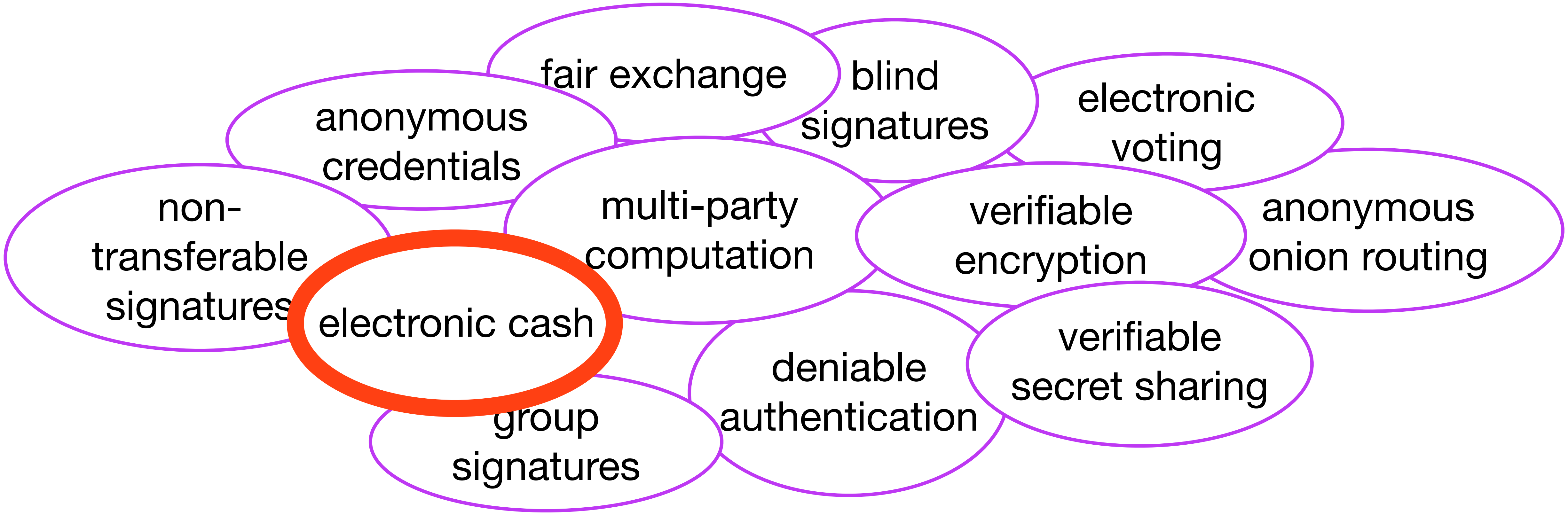

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electronic voting

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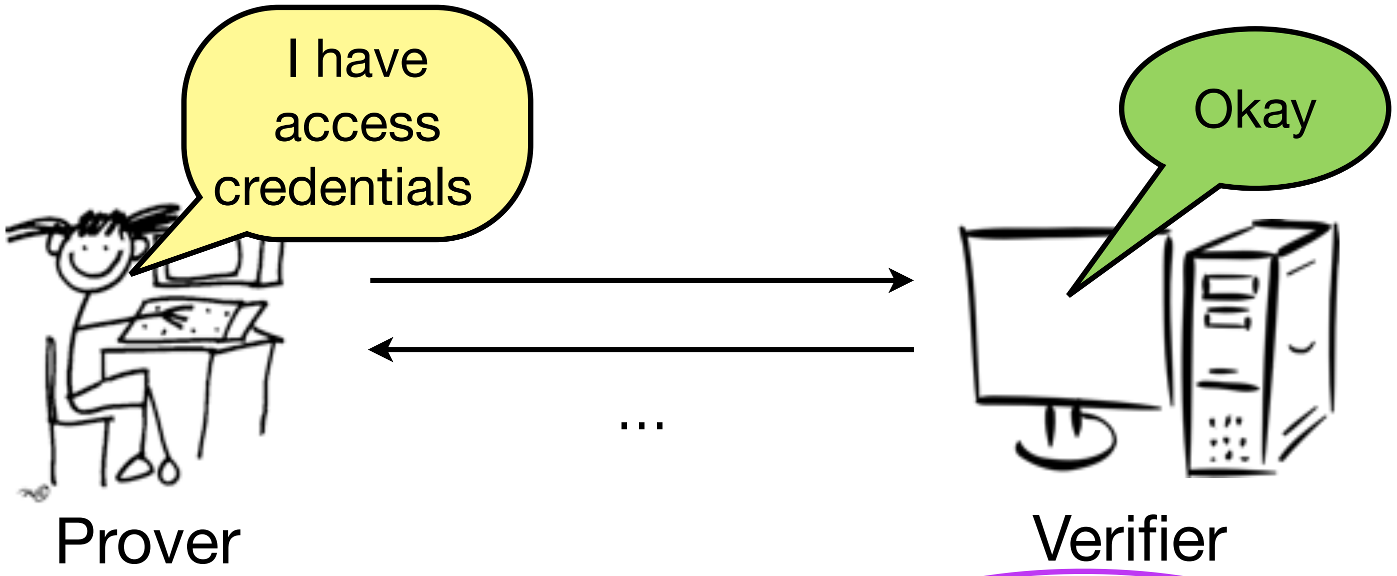

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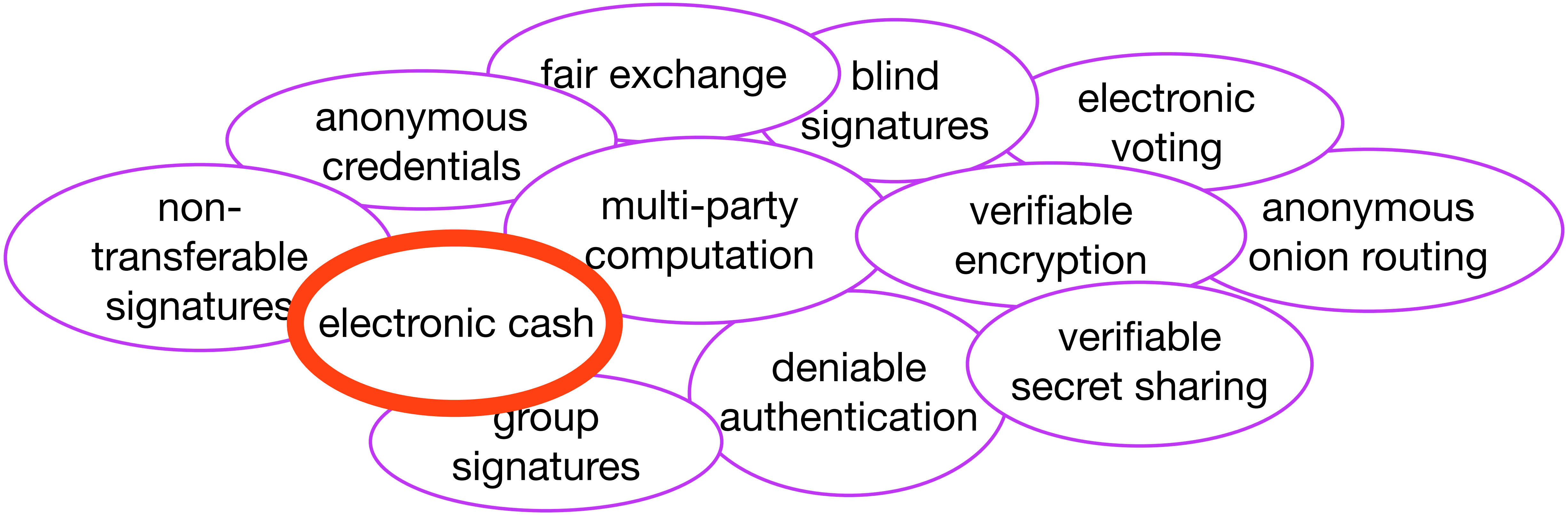

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blind signatures

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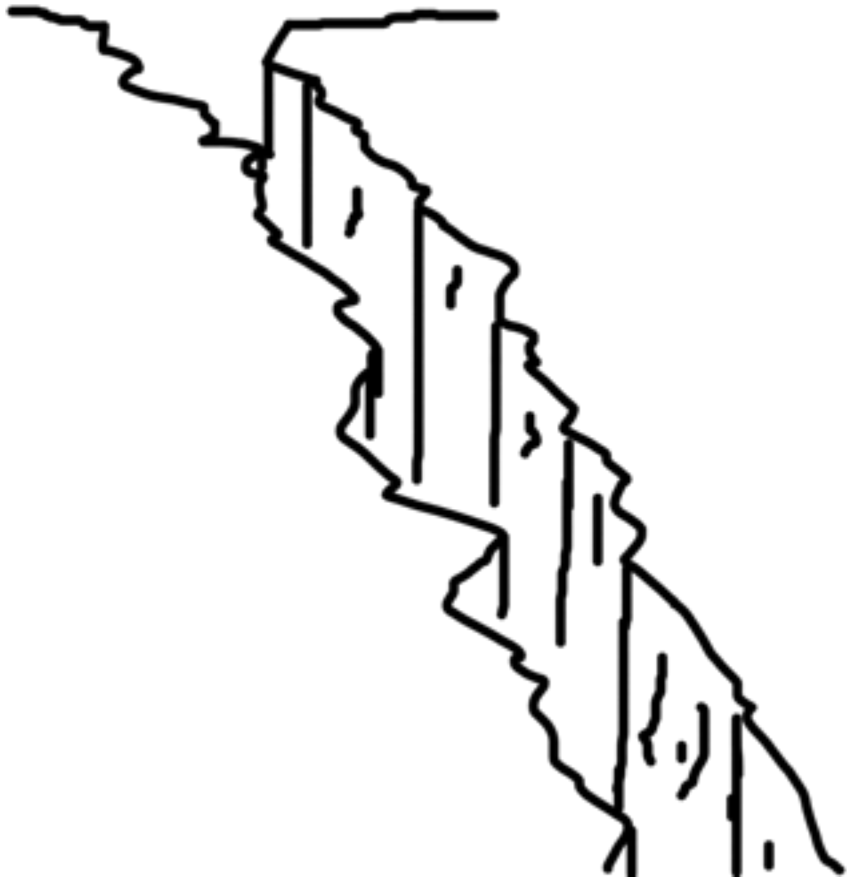
group signatures

Zero-knowledge proofs have applications, but can be complex

Implementing zero knowledge (take 1)

Crypto

Zero knowledge



Systems

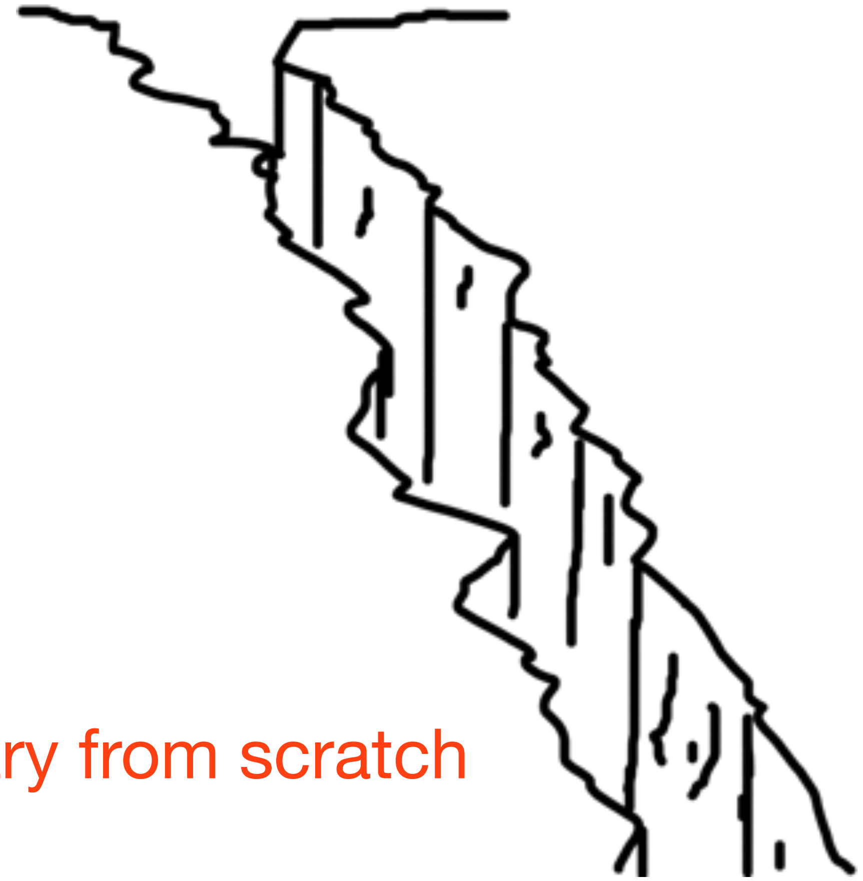
P2P file sharing

Implementing zero knowledge (take 1)

Crypto

Zero knowledge

Our first attempt: write library from scratch



Systems

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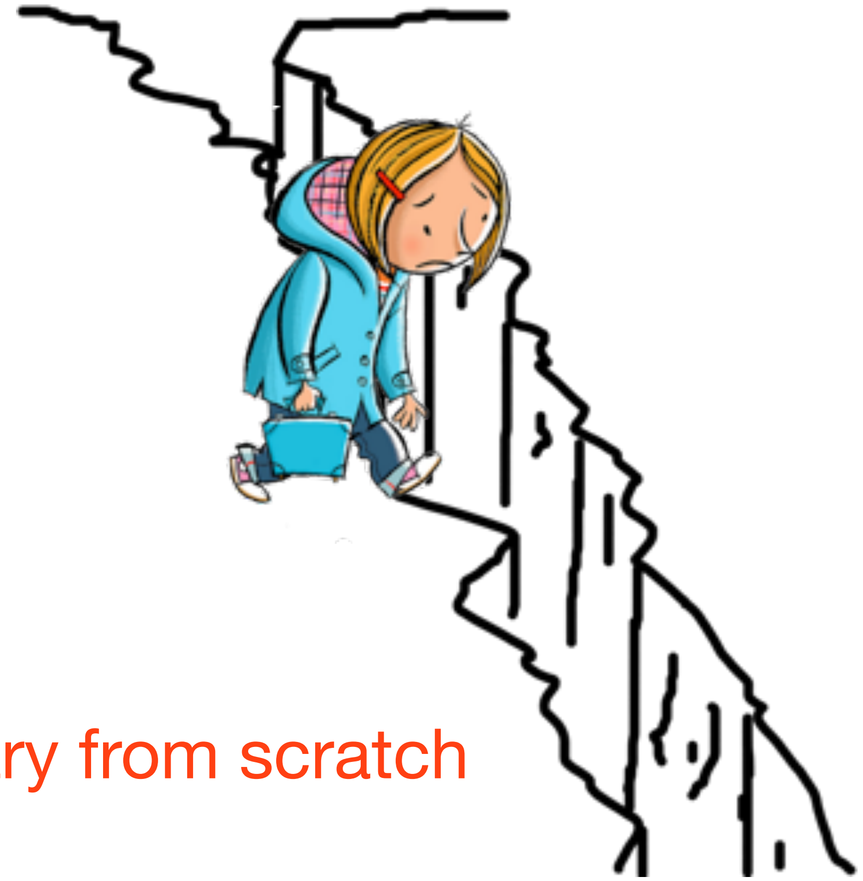

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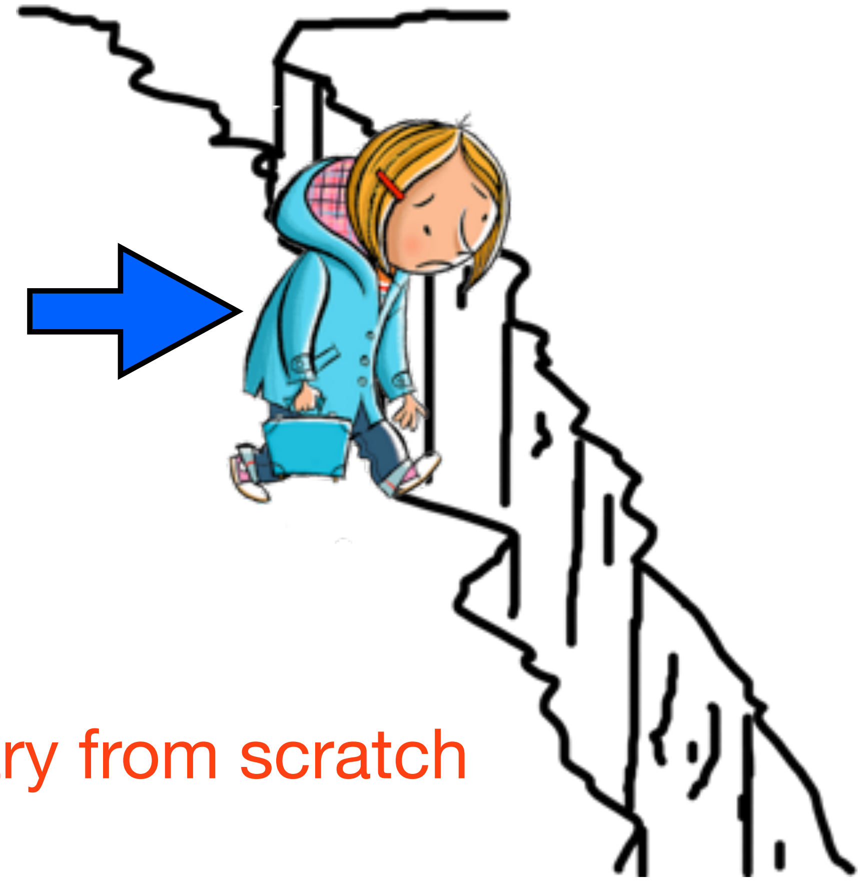

Systems

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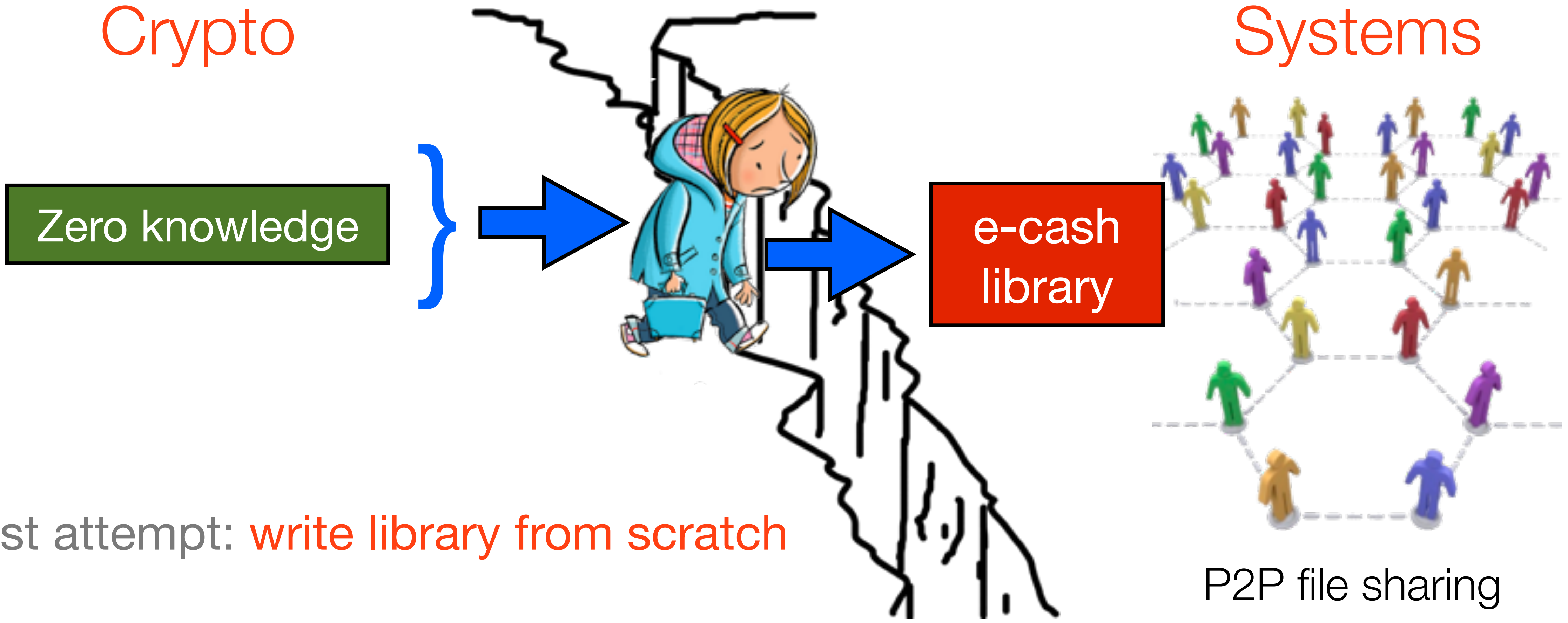

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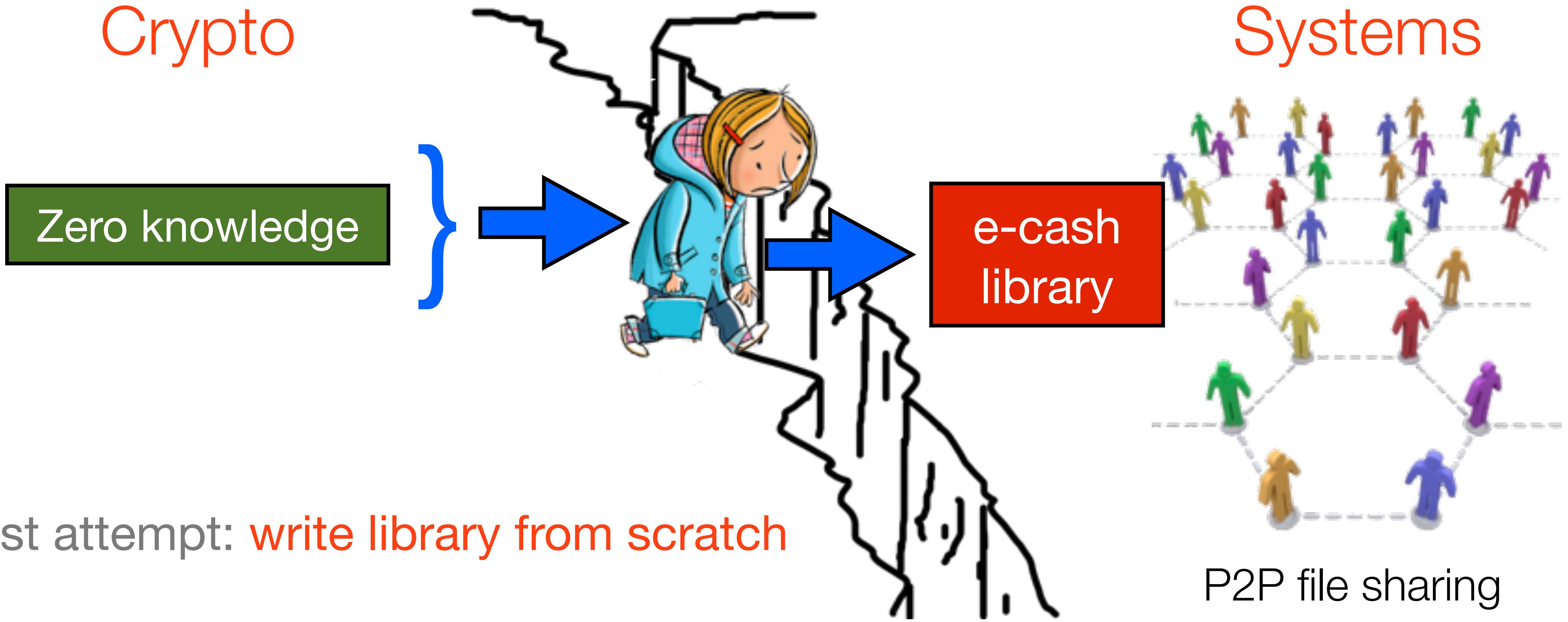

Our first attempt: write library from scratch

- Not reusable
- Time-consuming
- Error prone

Implementing zero knowledge (take 1)

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- Lesson learned: even though you know the math, coding can get messy

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```
Coin::Coin(const BankParameters *params, int stat, int lx,
  hashalg_t hashAlg, const ZZ &coinIndex, const ZZ
  &walletSize, int coinDenom, const ZZ &sk_u, const ZZ &s,
  const ZZ &t, const vec_ZZ &clSig, const vector<SecretValue>
  &clPrivateSecrets, const vector<SecretValue>
  &clPrivateRandoms, const ZZ &r) { ...
```

Implementing zero knowledge (take 1)

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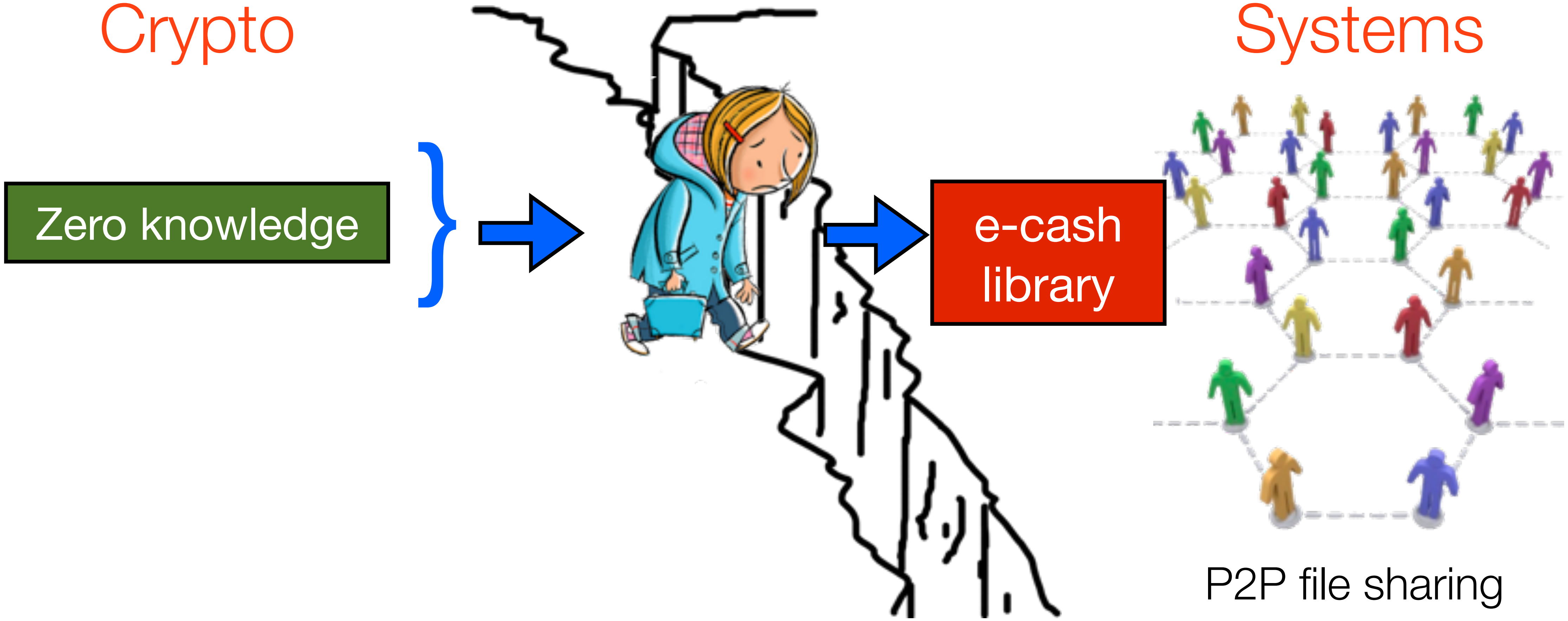
- Functionality is there, but not easy to use

Implementing zero knowledge (take 2)

Crypto

Systems



Zero knowledge

e-cash library

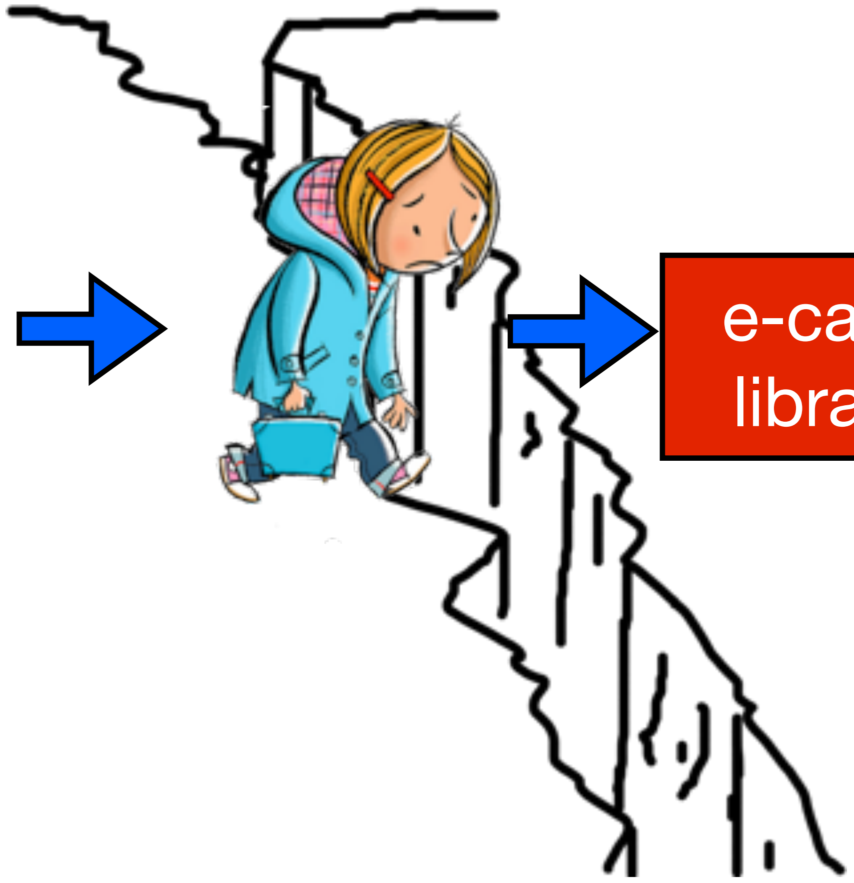
P2P file sharing

Implementing zero knowledge (take 2)

Crypto

Systems

Zero knowledge

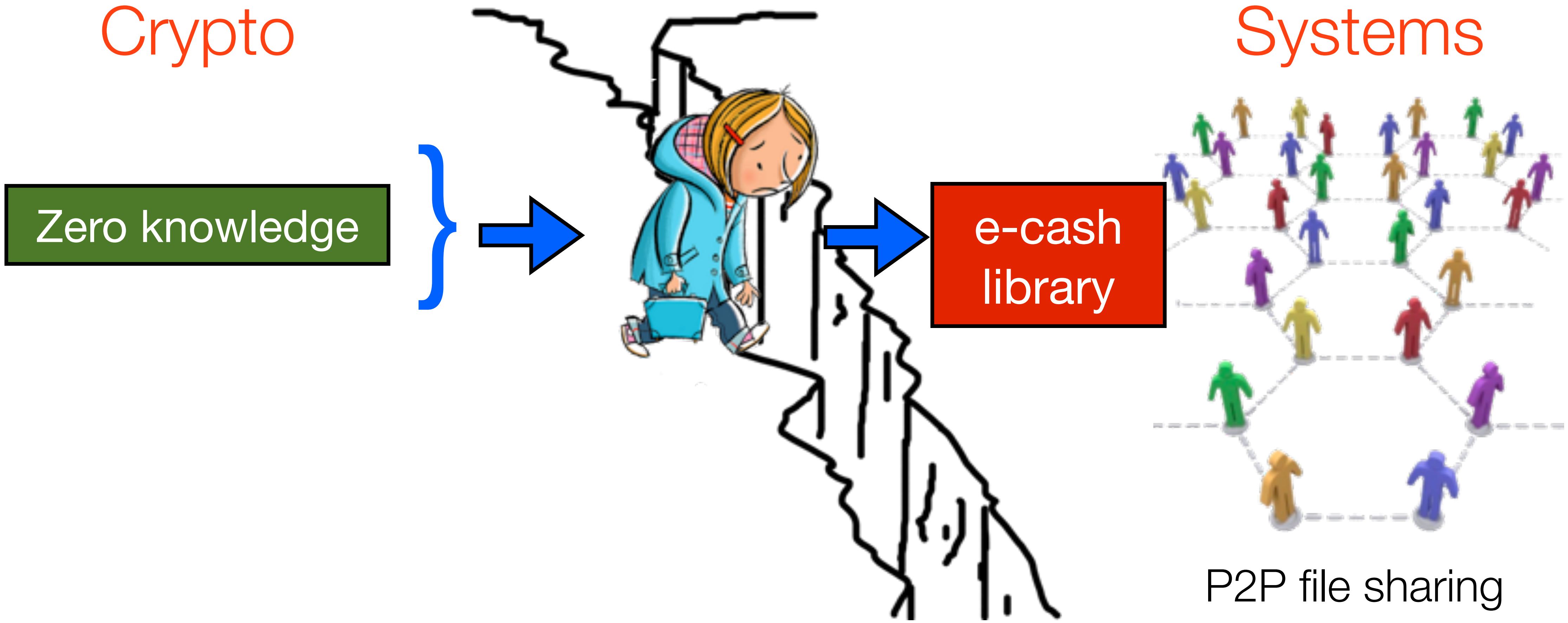


e-cash library

P2P file sharing

How can we lighten the implementation load?

Implementing zero knowledge (take 2)



Crypto

Zero knowledge

e-cash library

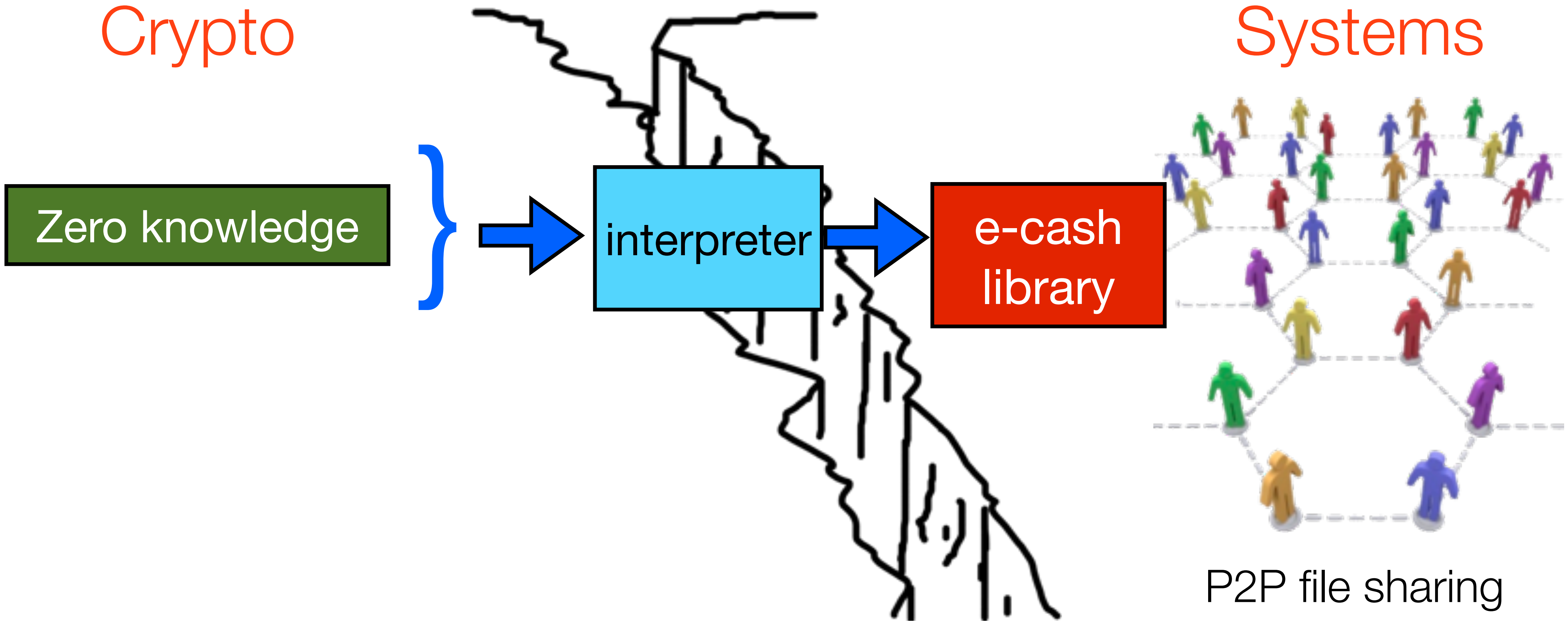
Systems

P2P file sharing

How can we lighten the implementation load?

- Design a language: ZKPDL (Zero Knowledge Proof Description Language)
- Build an interpreter to automatically translate from ZKPDL to proofs

Implementing zero knowledge (take 2)



Crypto

Systems

Zero knowledge

interpreter

e-cash library

P2P file sharing

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Step 1: writing programs in ZKPDL

High-level language, goal was to mirror theoretical descriptions

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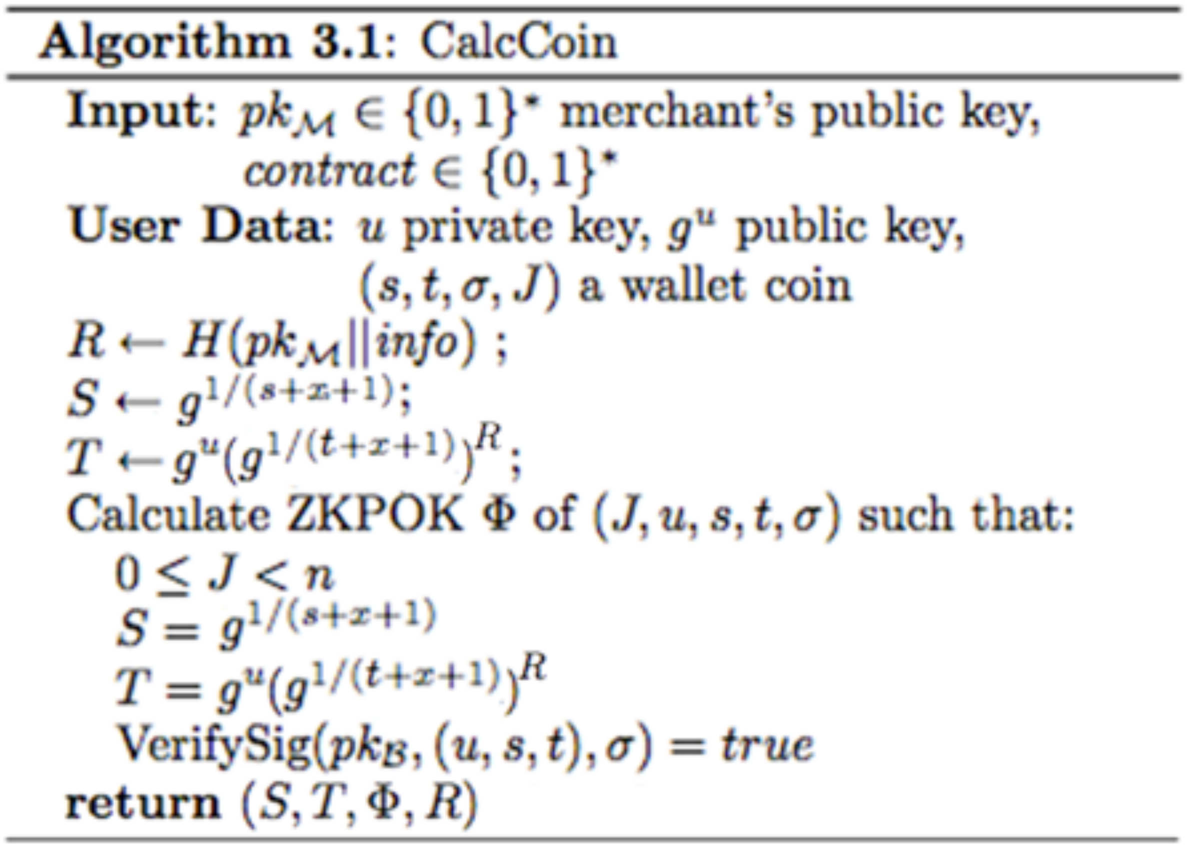
High-level language, goal was to mirror theoretical descriptions

Description in paper



```
Algorithm 3.1: CalcCoin
  Input: $pk_{\mathcal{M}} \in \{0,1\}^*$ merchant's public key,
         $contract \in \{0,1\}^*$
  User Data: $u$ private key, $g^u$ public key,
             $(s, t, \sigma, J)$ a wallet coin
  $R \leftarrow H(pk_{\mathcal{M}} || info)$ ;
  $S \leftarrow g^{1/(s+x+1)}$;
  $T \leftarrow g^u (g^{1/(t+x+1)})^R$;
  Calculate ZKPOK $\Phi$ of $(J, u, s, t, \sigma)$ such that:
    $0 \leq J < n$
    $S = g^{1/(s+x+1)}$
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    $\mathrm{VerifySig}(pk_{\mathcal{B}}, (u, s, t), \sigma) = true$
  return $(S, T, \Phi, R)$
```

Step 1: writing programs in ZKPDL

High-level language, goal was to mirror theoretical descriptions

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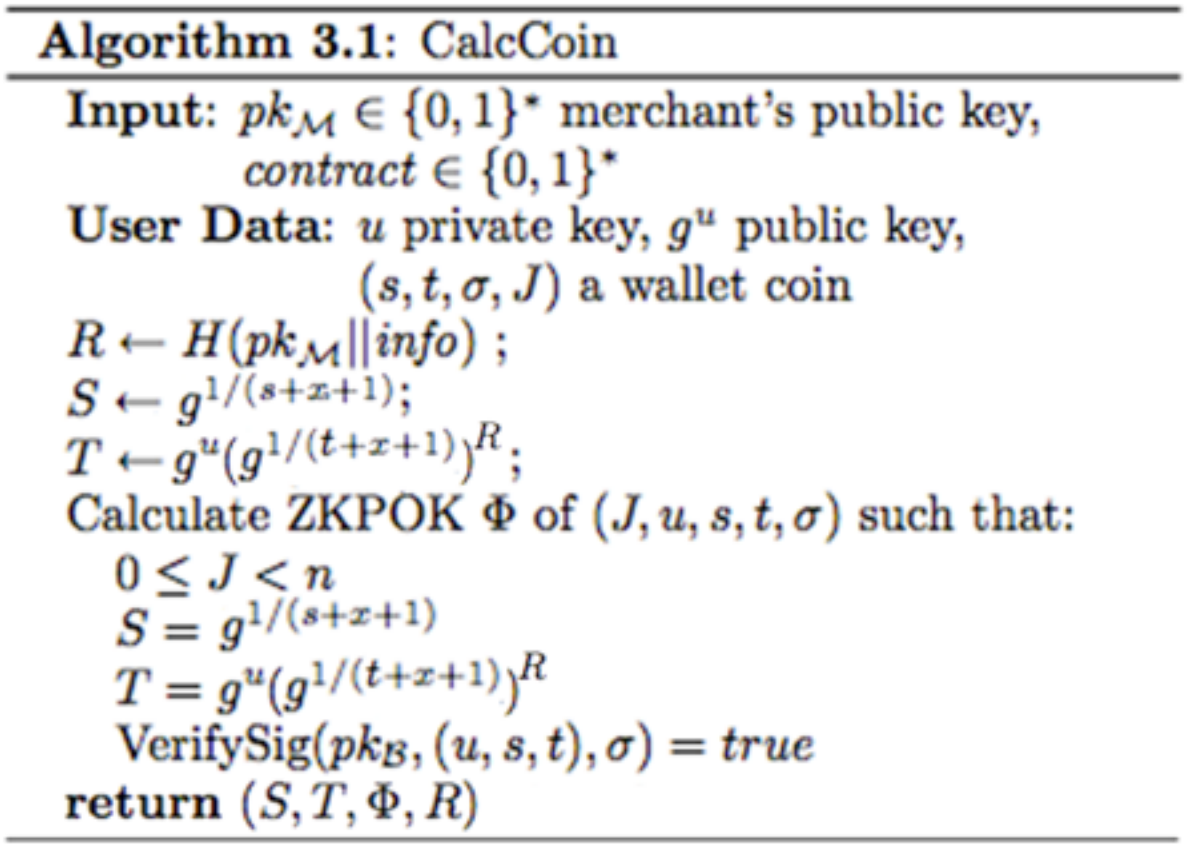

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Description in ZKPDL

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computation:
  ...
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    T := g^u * (g^(1/(t+x+1)))^R
proof:
  given:
    group: G = <g,h>
    elements in G: S, T
  prove knowledge of:
    exponents in G: u,s,t,x
    integer: J
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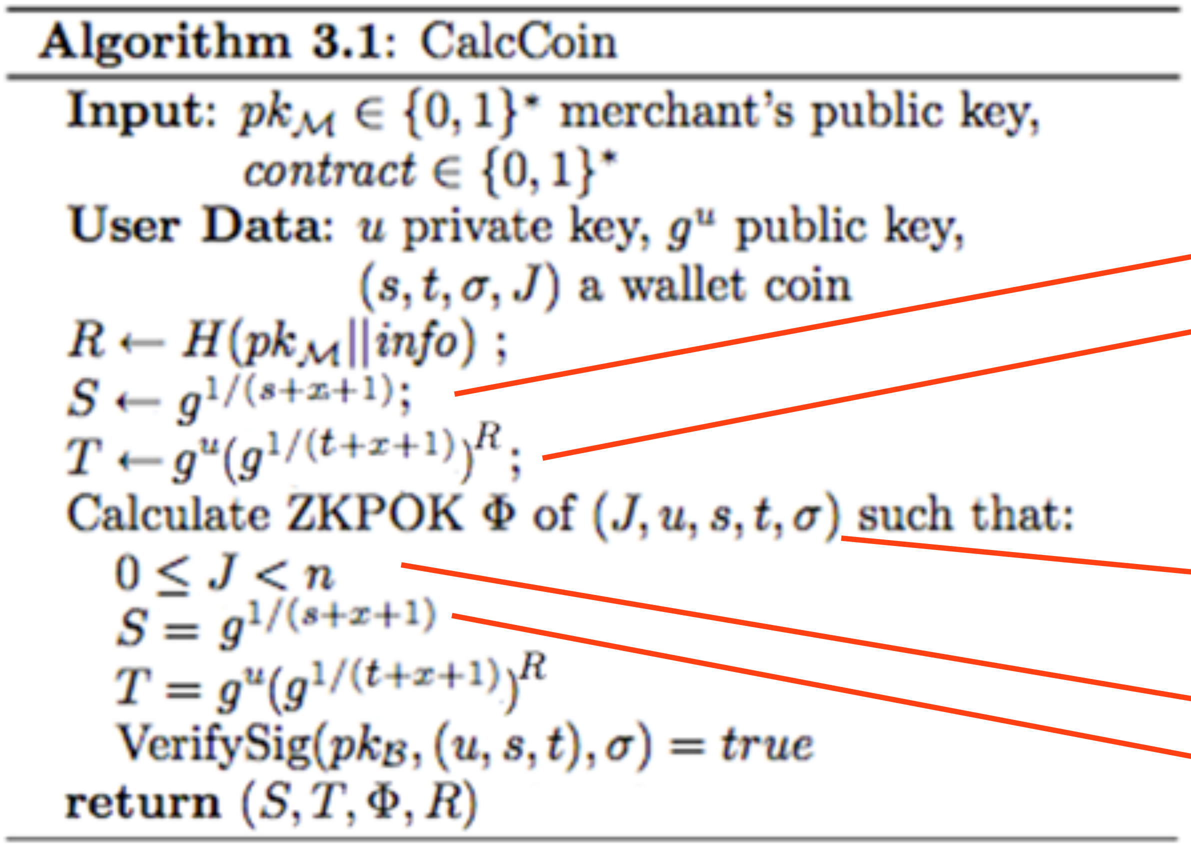

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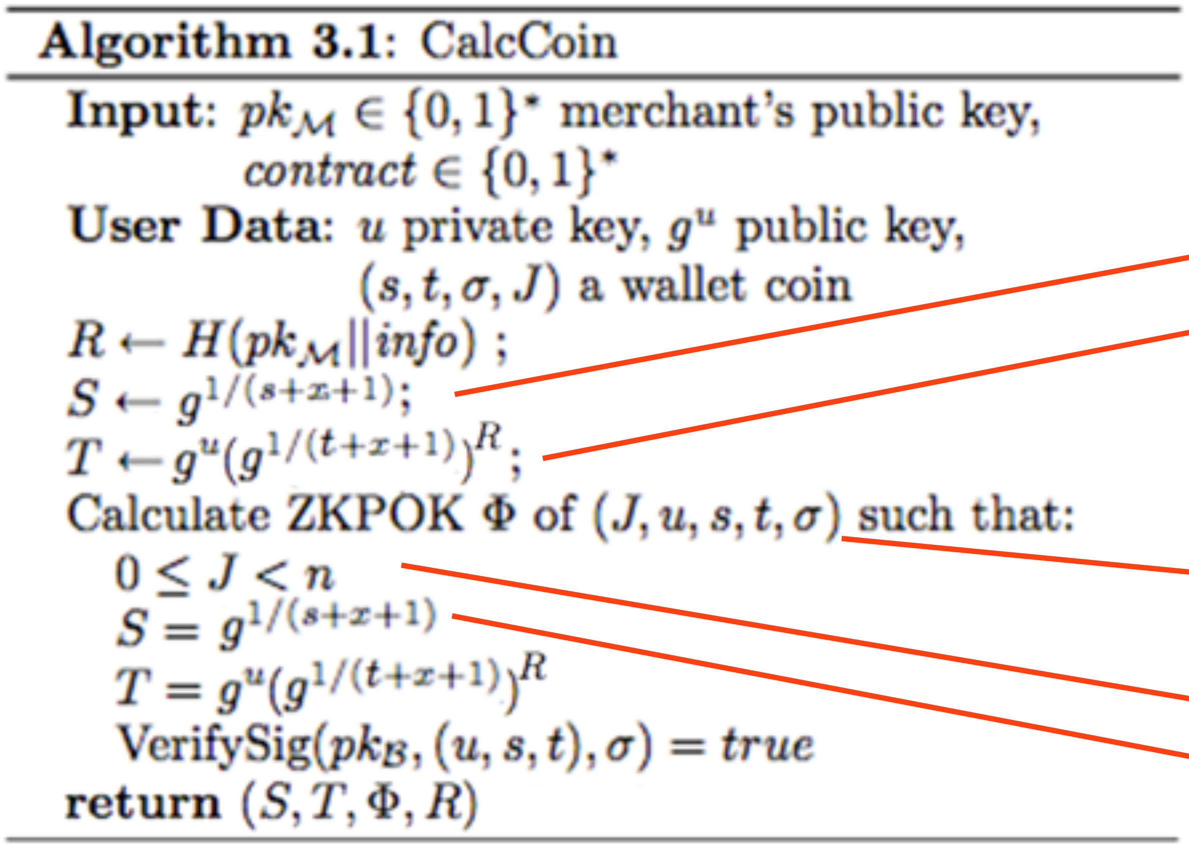

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Currently support four ZKP types, enough for vast majority of applications

Should also be easy to add new types if they're needed

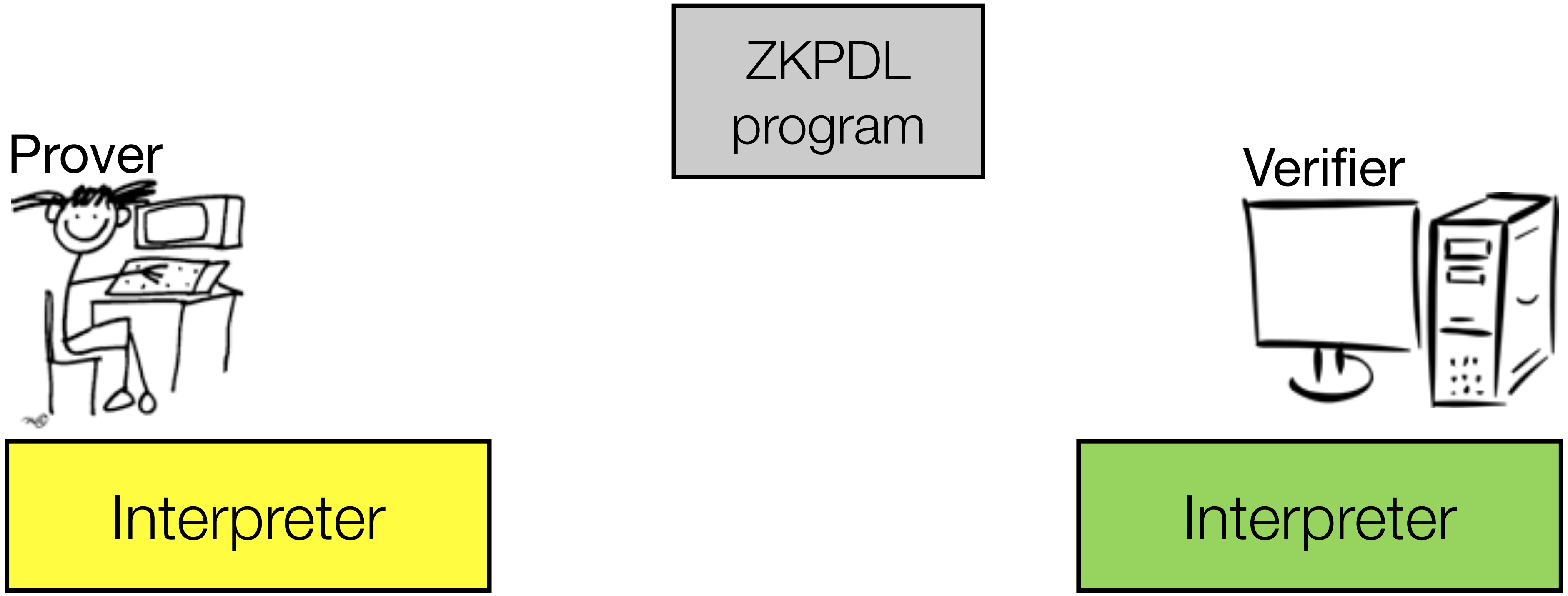
Sample usage of the interpreter

Prover

I have access credentials

Verifier

Sample usage of the interpreter



ZKPDL program

Prover

Verifier

Interpreter

Interpreter

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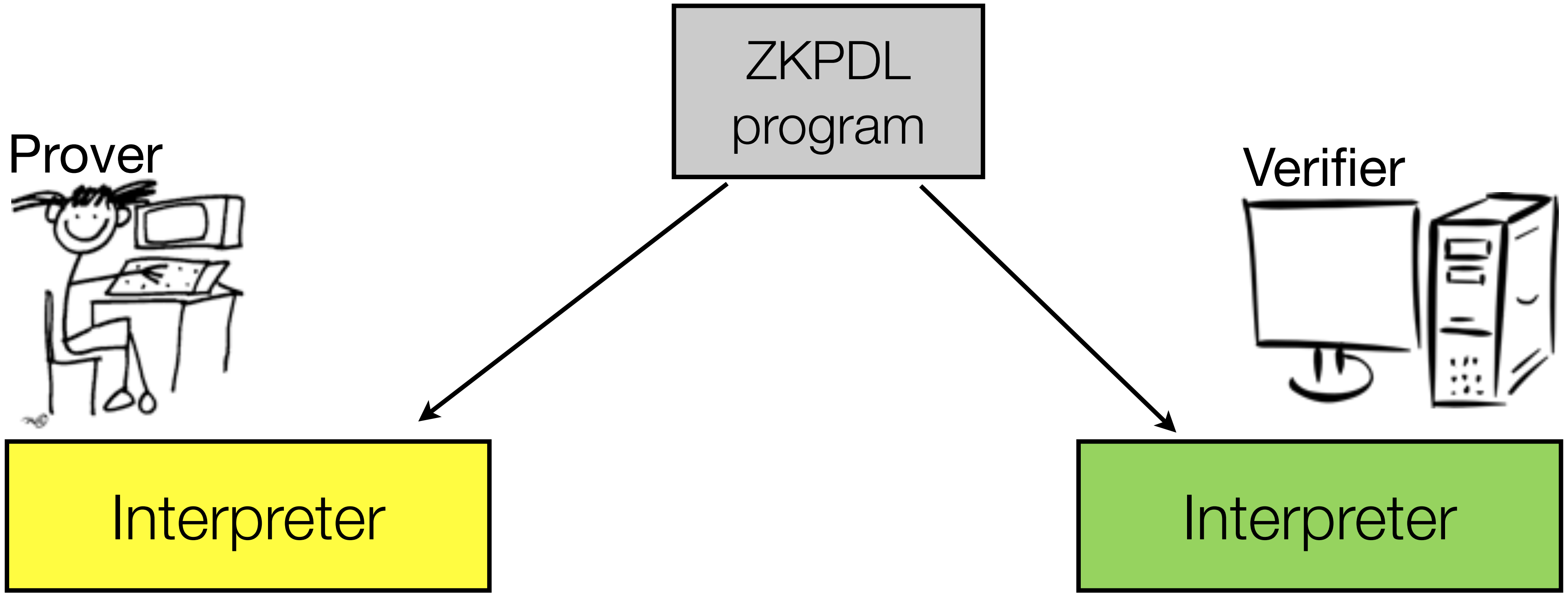

- At compile time, check program syntax, types, etc.

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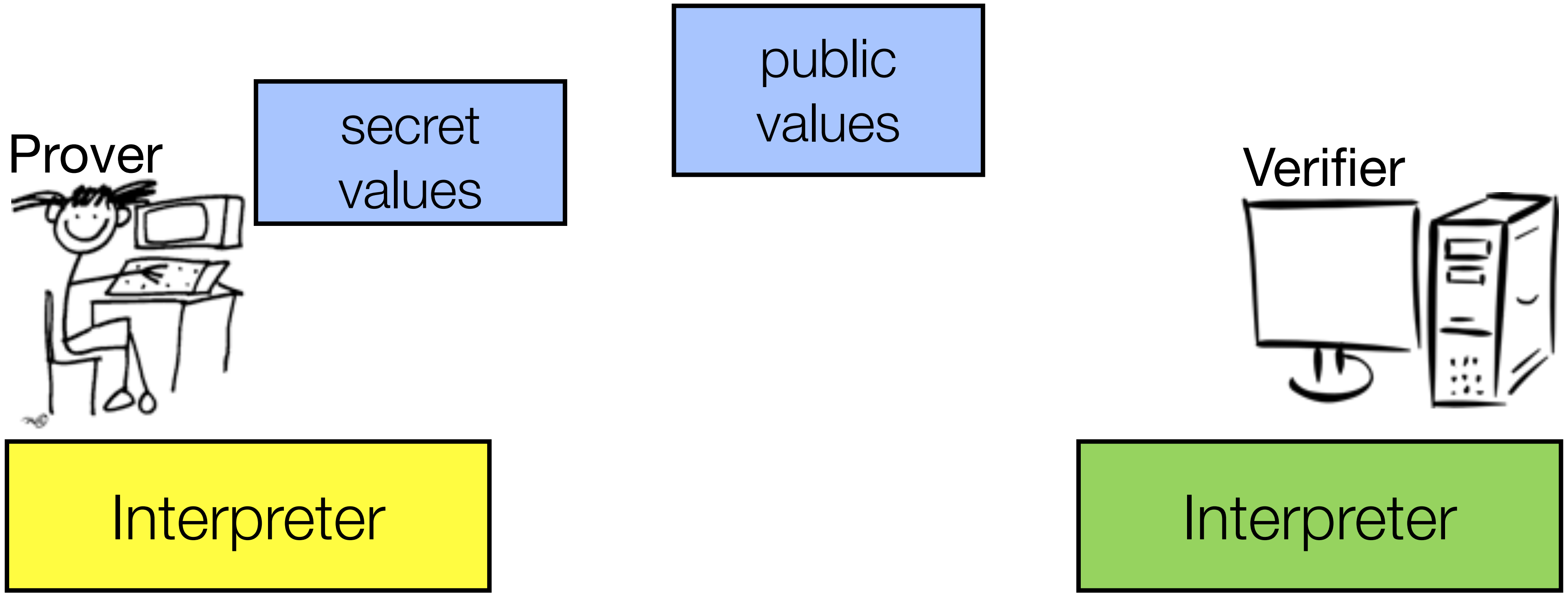


Prover

secret values

public values

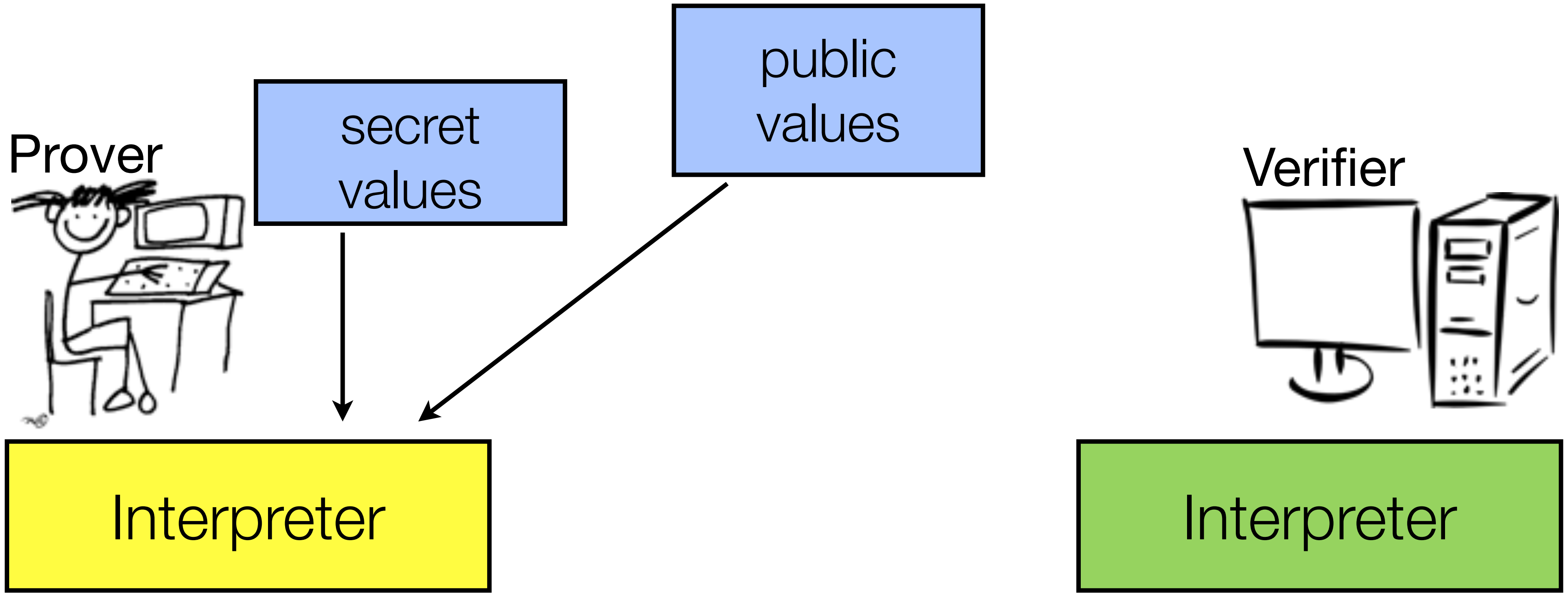
Verifier

Interpreter

Interpreter

- At compile time, check program syntax, types, etc.
- At run time, need all values to be proved

Sample usage of the interpreter



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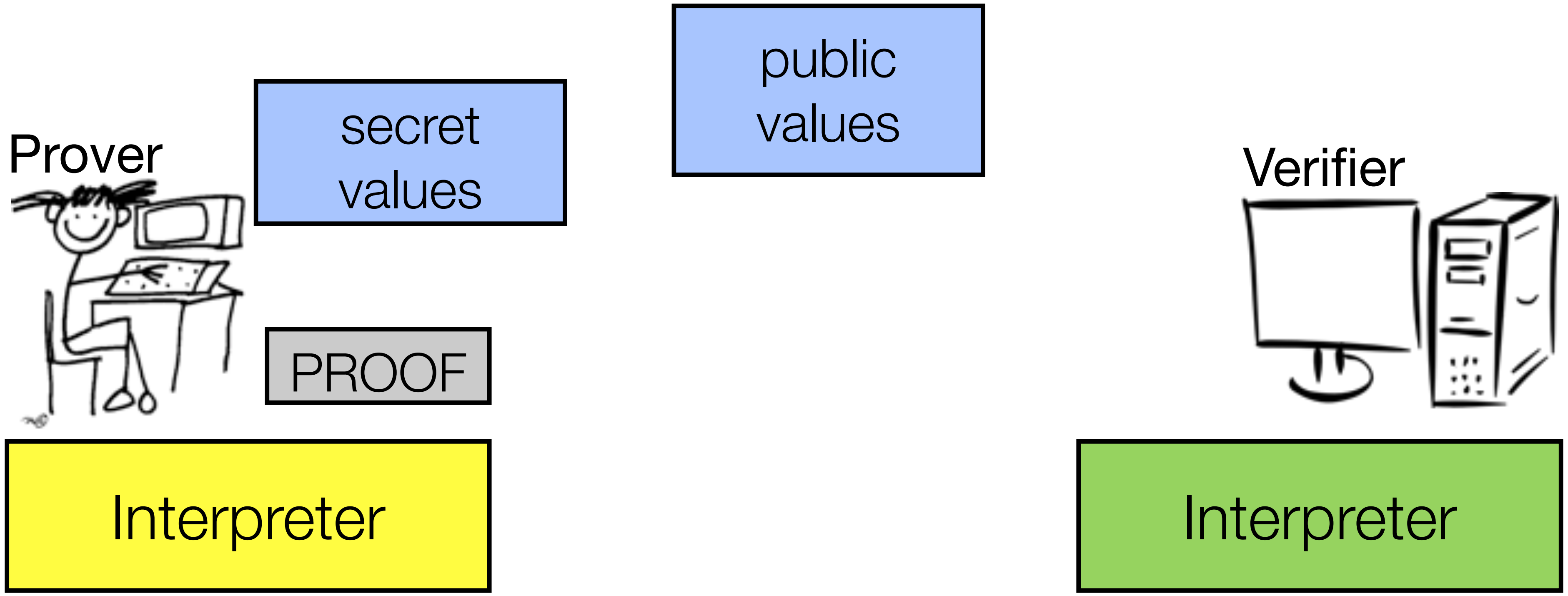

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secret values

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Verifier

PROOF

Interpreter

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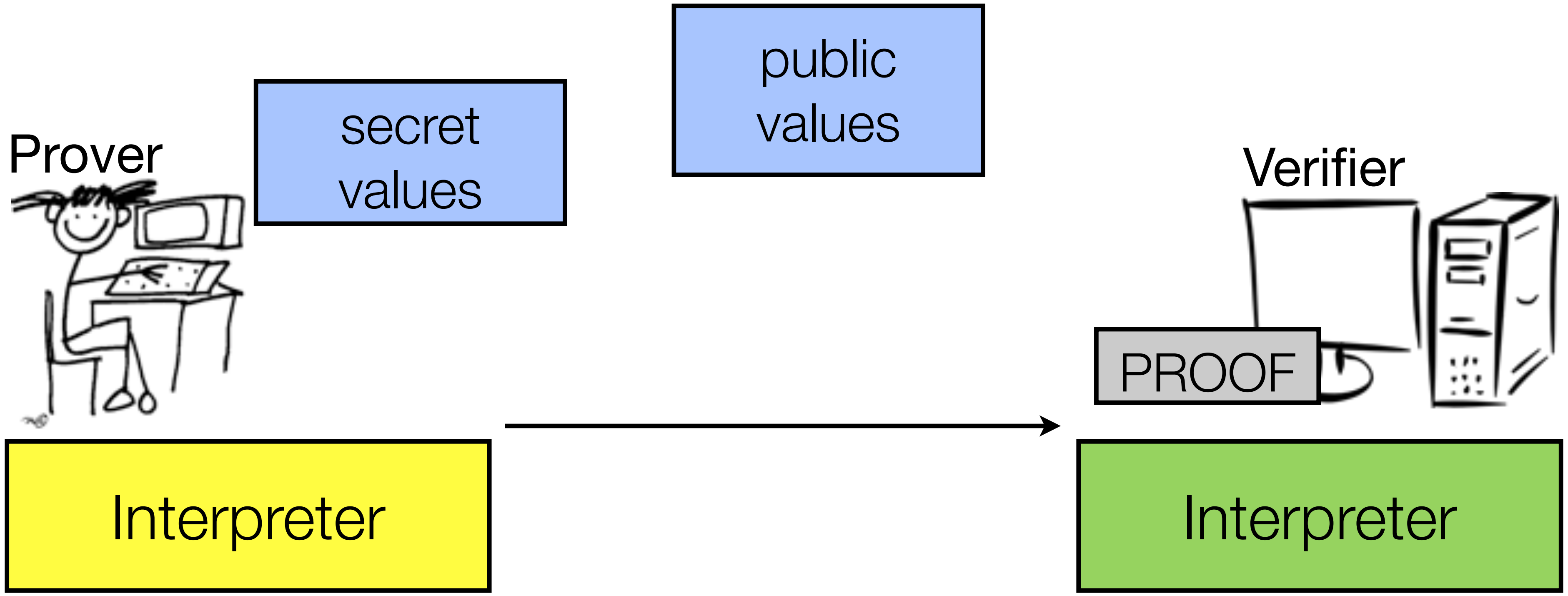

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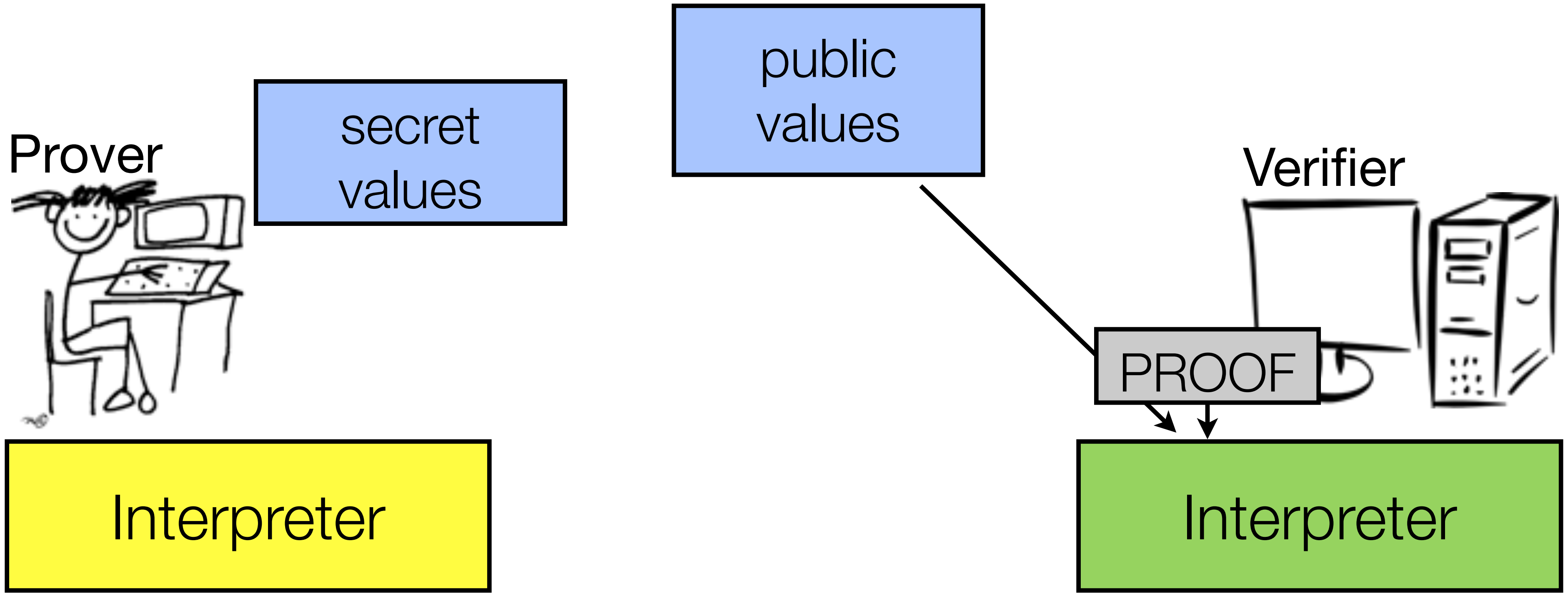

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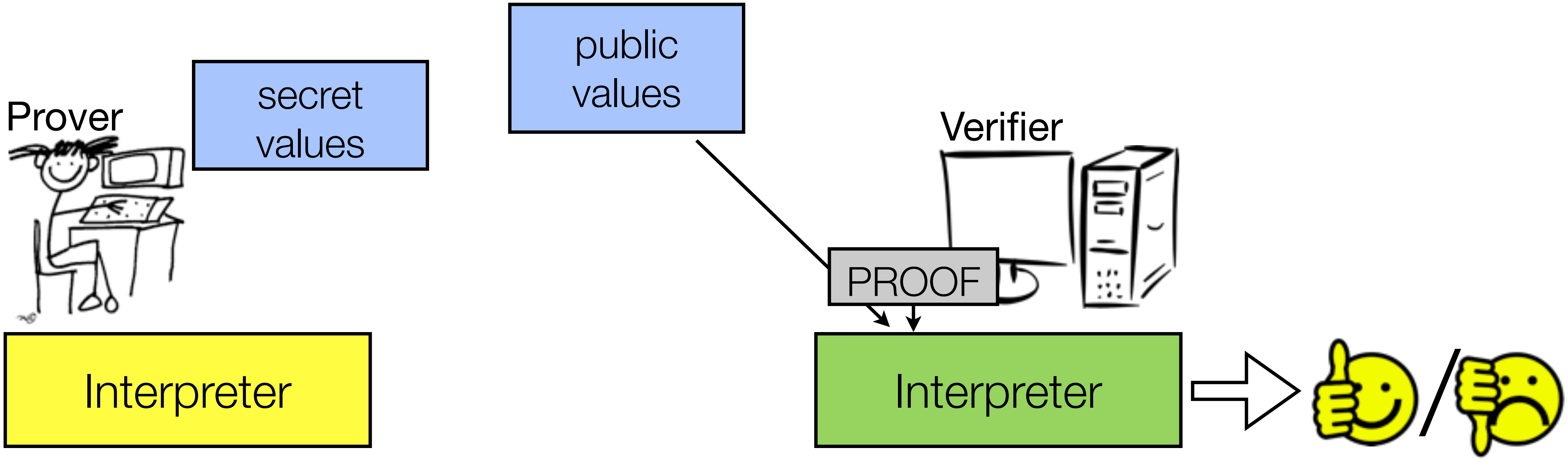

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Step 2: using the interpreter to write a library

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Use simple procedure to create wrapper classes for interpreter

Step 2: using the interpreter to write a library

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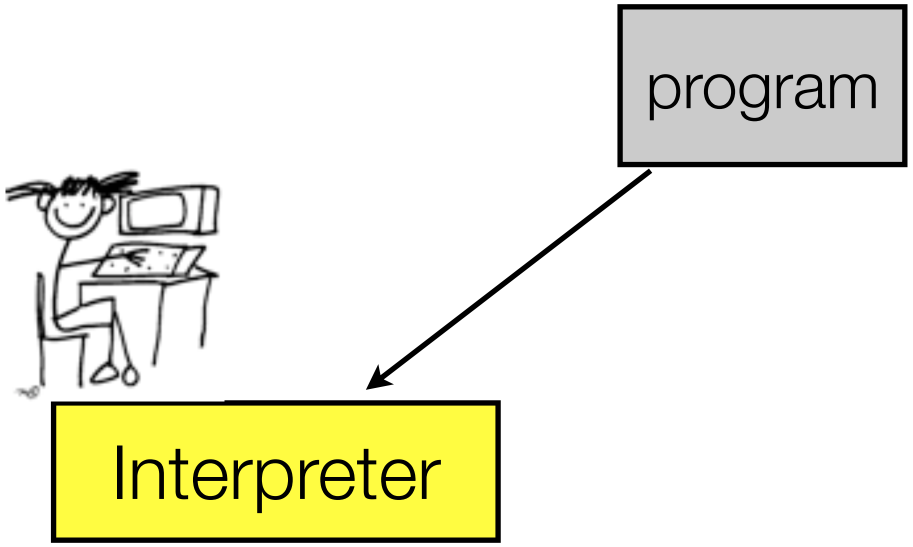

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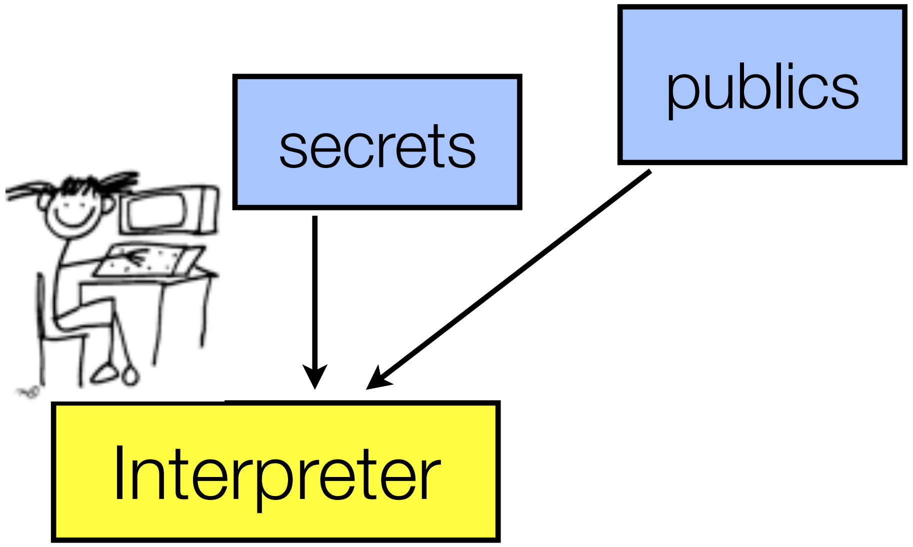

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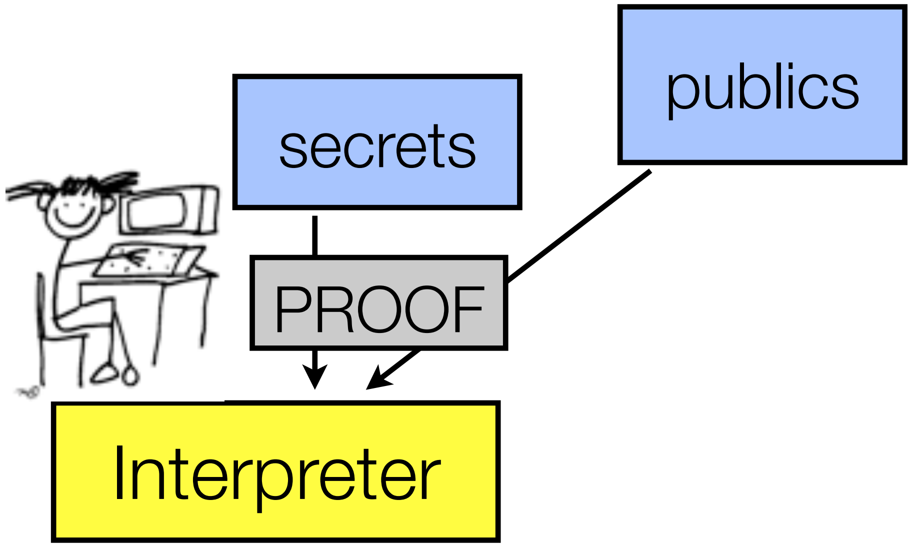

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Took 3-4 months to build interpreter, then one month to reconstruct library

Optimizations: caching

In addition to usability, can achieve improvements in efficiency

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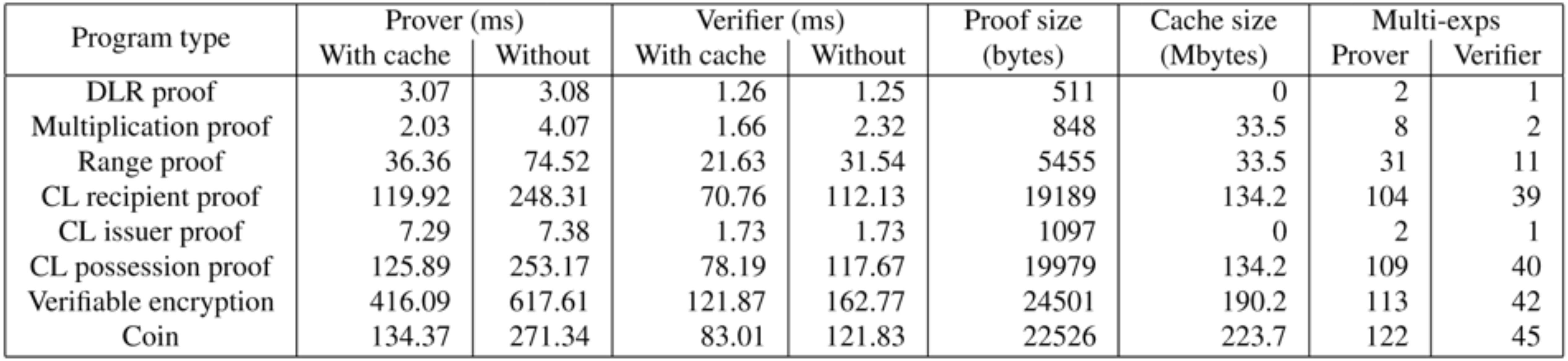
- Save copy of interpreter state after compilation

Did caching help?



Program type	Prover (ms)		Verifier (ms)		Proof size	Cache size	Multi-exps	
	With cache	Without	With cache	Without	(bytes)	(Mbytes)	Prover	Verifier
DLR proof	3.07	3.08	1.26	1.25	511	0	2	1
Multiplication proof	2.03	4.07	1.66	2.32	848	33.5	8	2
Range proof	36.36	74.52	21.63	31.54	5455	33.5	31	11
CL recipient proof	119.92	248.31	70.76	112.13	19189	134.2	104	39
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CL possession proof	125.89	253.17	78.19	117.67	19979	134.2	109	40
Verifiable encryption	416.09	617.61	121.87	162.77	24501	190.2	113	42
Coin	134.37	271.34	83.01	121.83	22526	223.7	122	45

On the prover side, saw about a 50% speed-up using all optimizations

On the verifier side, about 30% (less computation)

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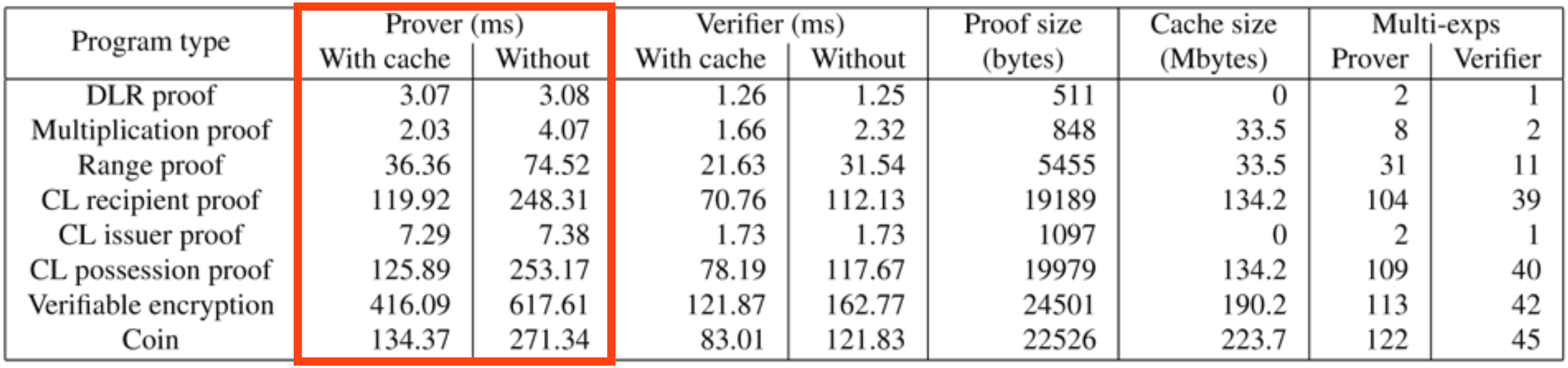

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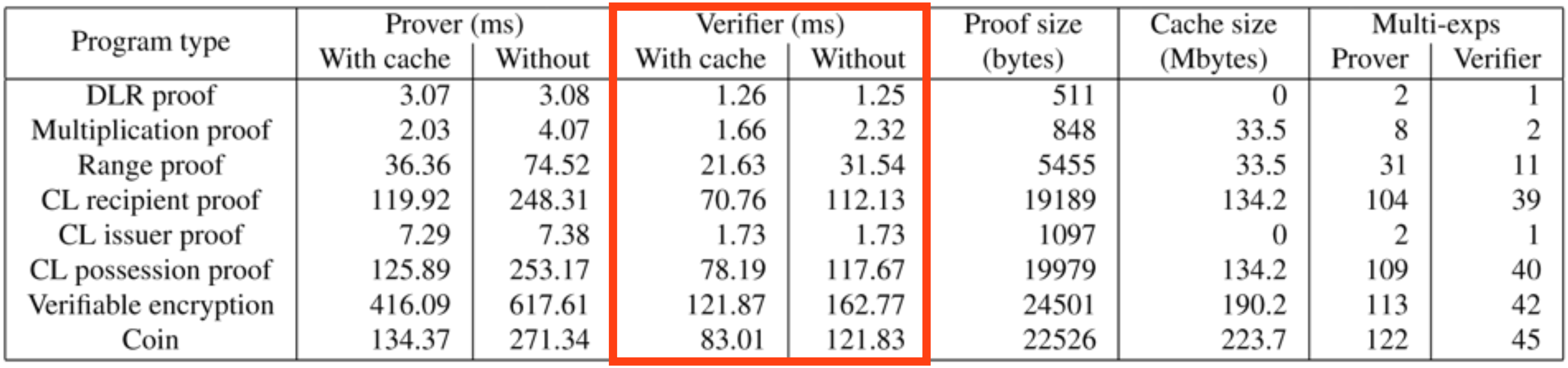

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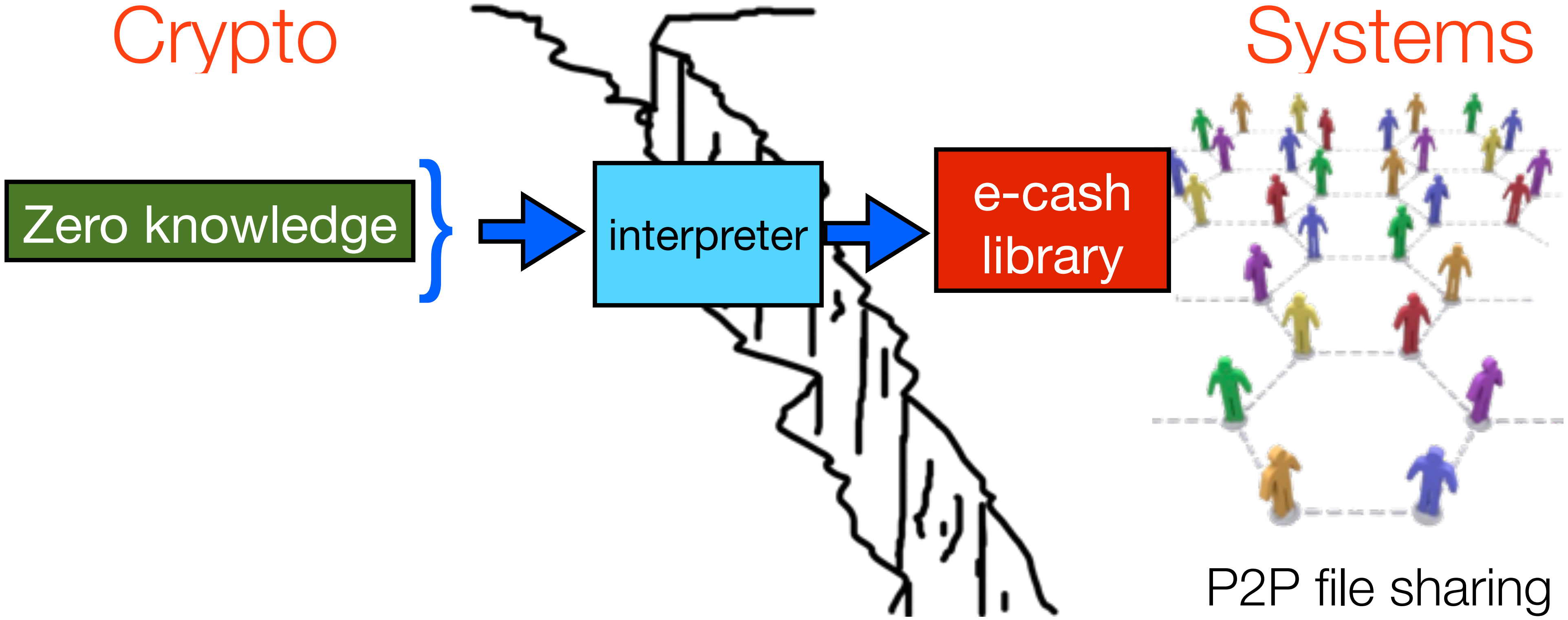
Case study: using ZKPDL for e-cash



Crypto

Systems

Zero knowledge

interpreter

e-cash library

P2P file sharing

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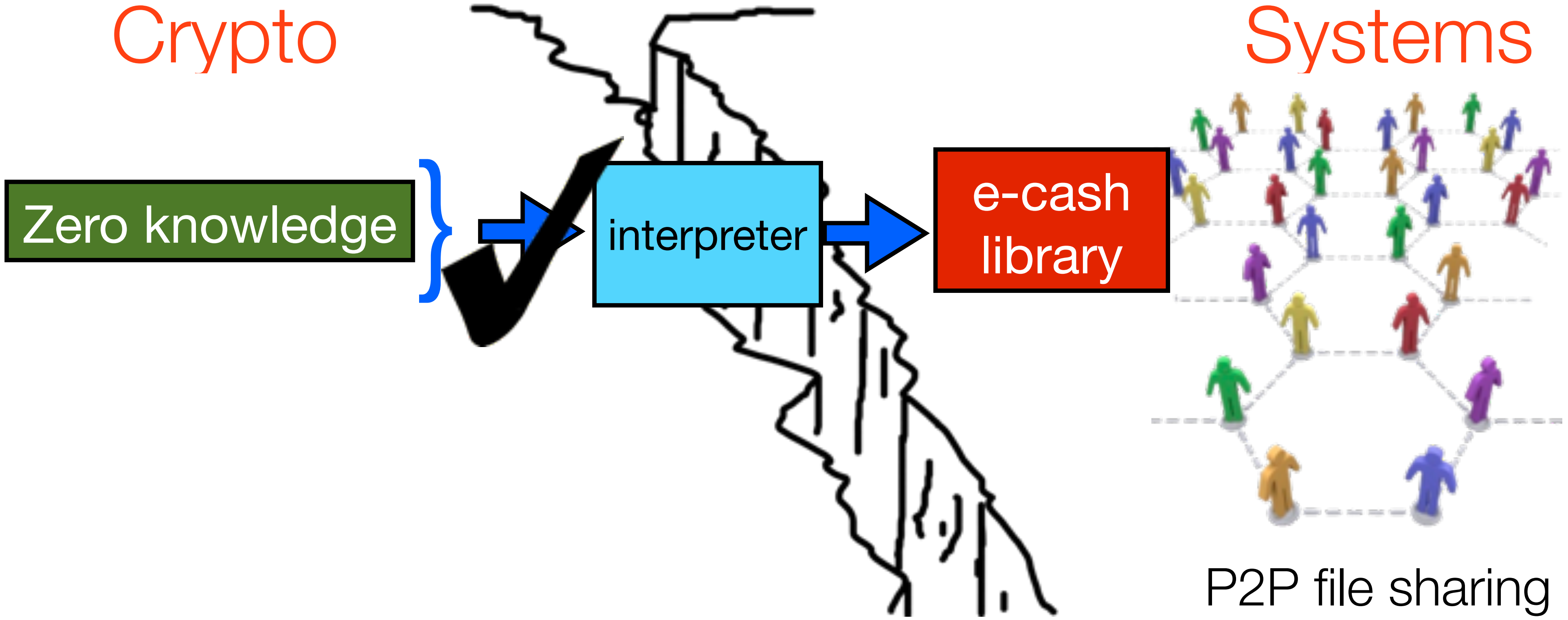

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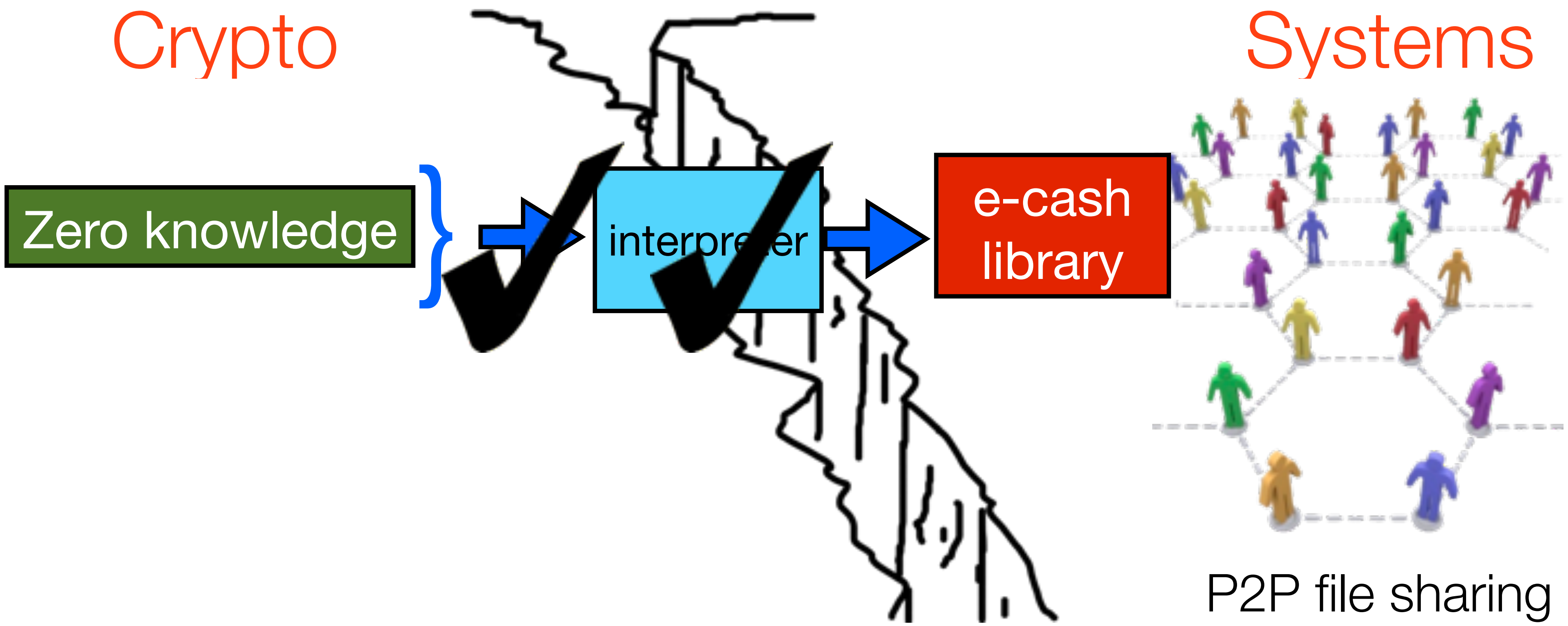

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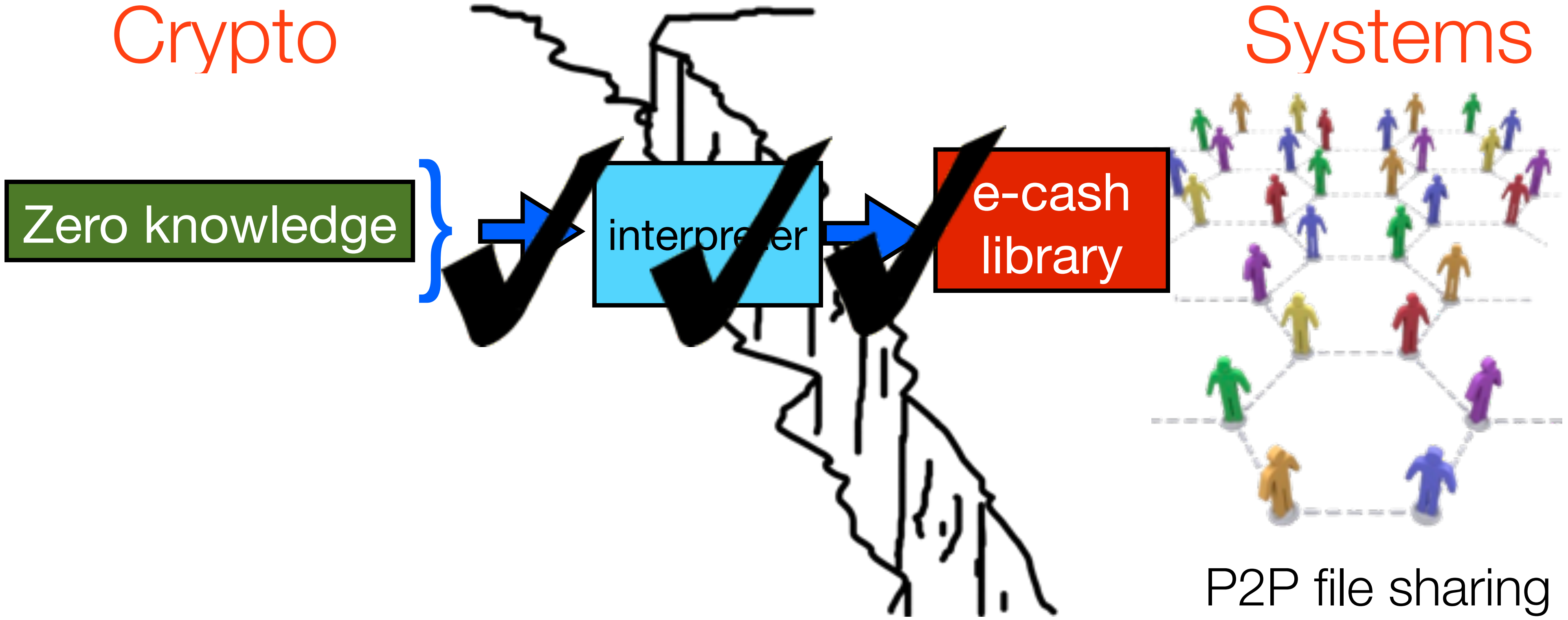

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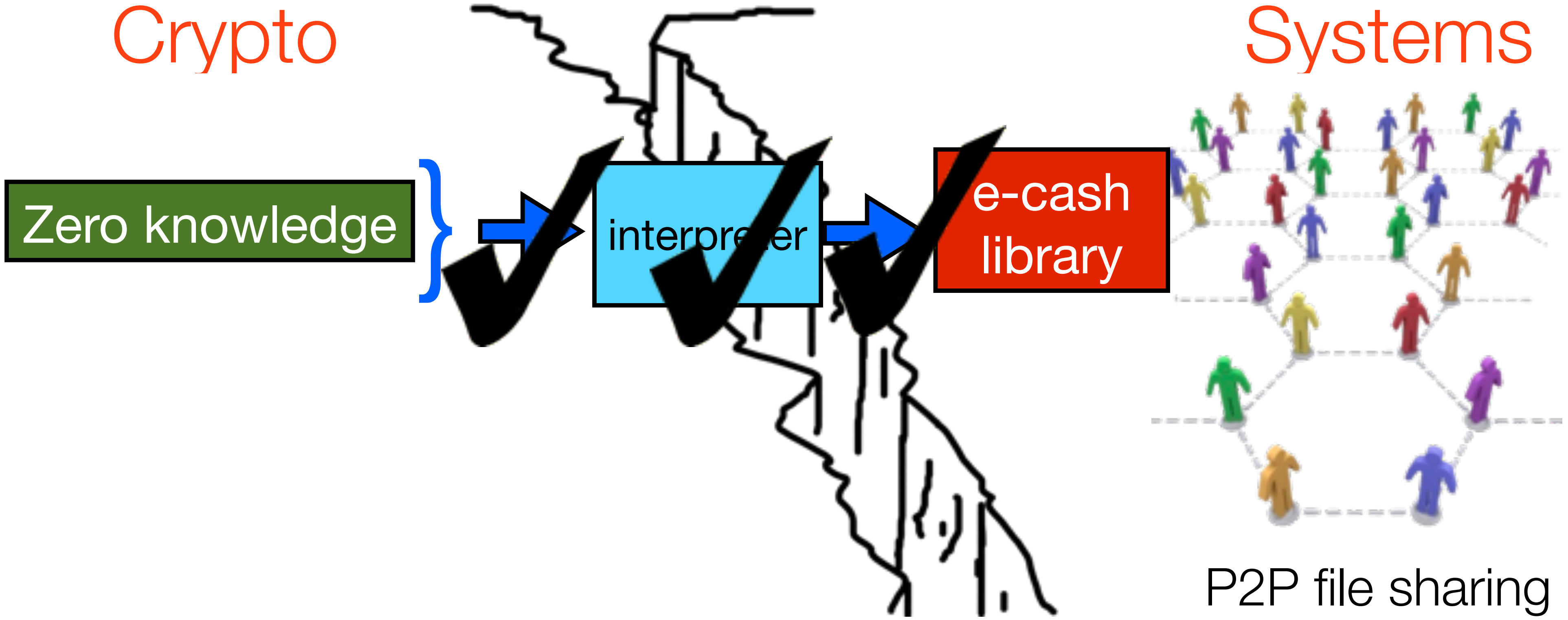

P2P file sharing

E-cash was originally developed [Ch82] as replacement for currency

Now, view e-cash in context of token systems

- Our usage in P2P file-sharing schemes [BCE+07]
- Provides anonymous transportation ticketing (future work)

How e-cash works [Ch82, CHL05, CLM07]

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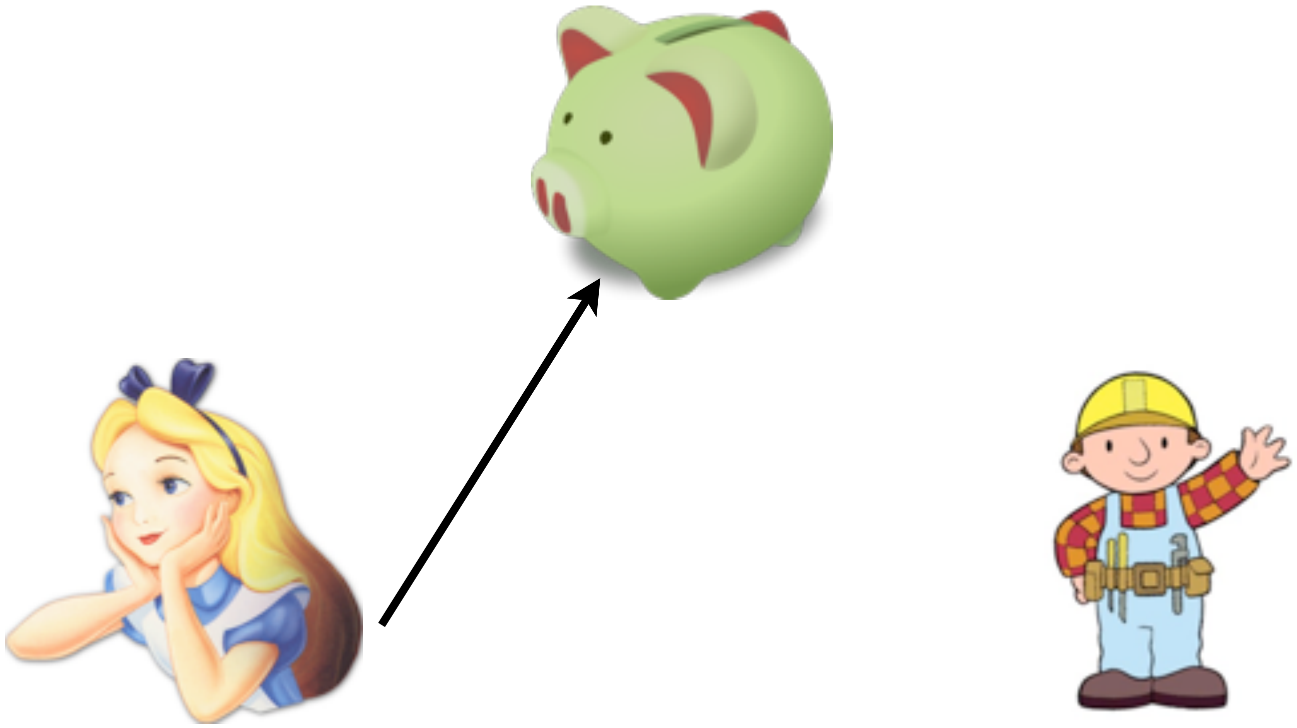

Withdraw: Alice gets coins from bank

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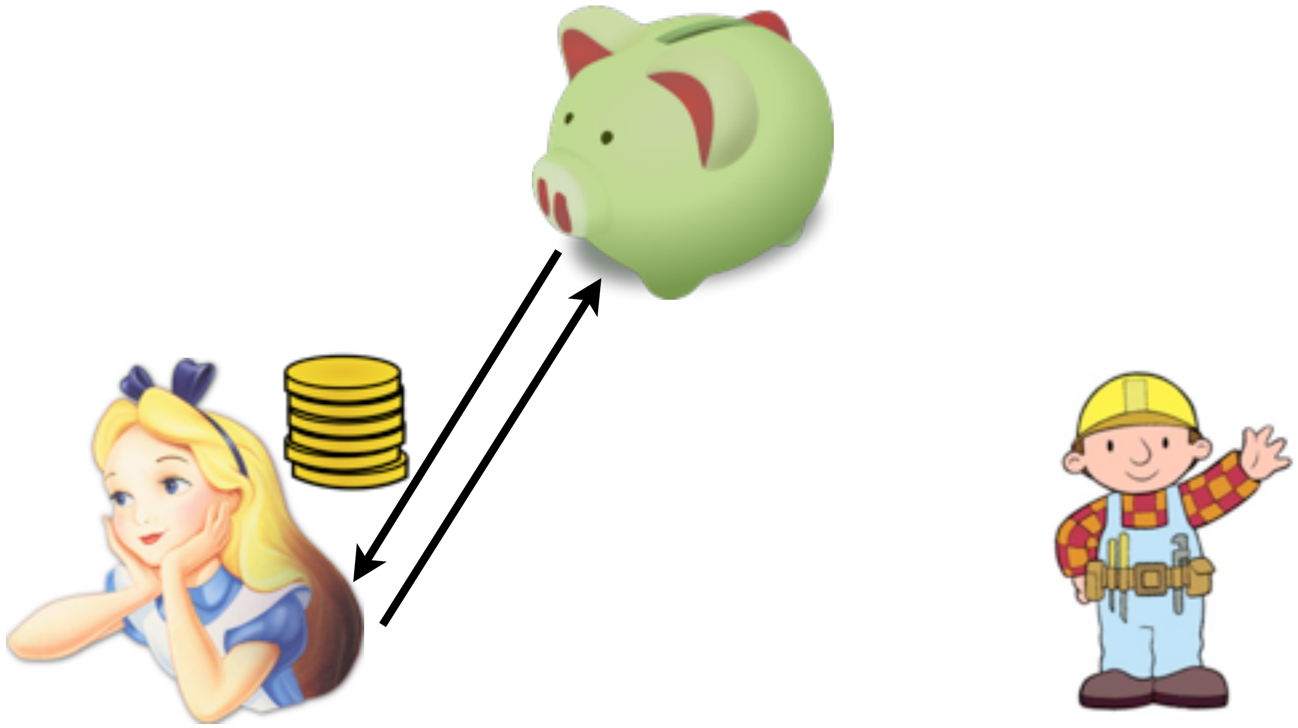

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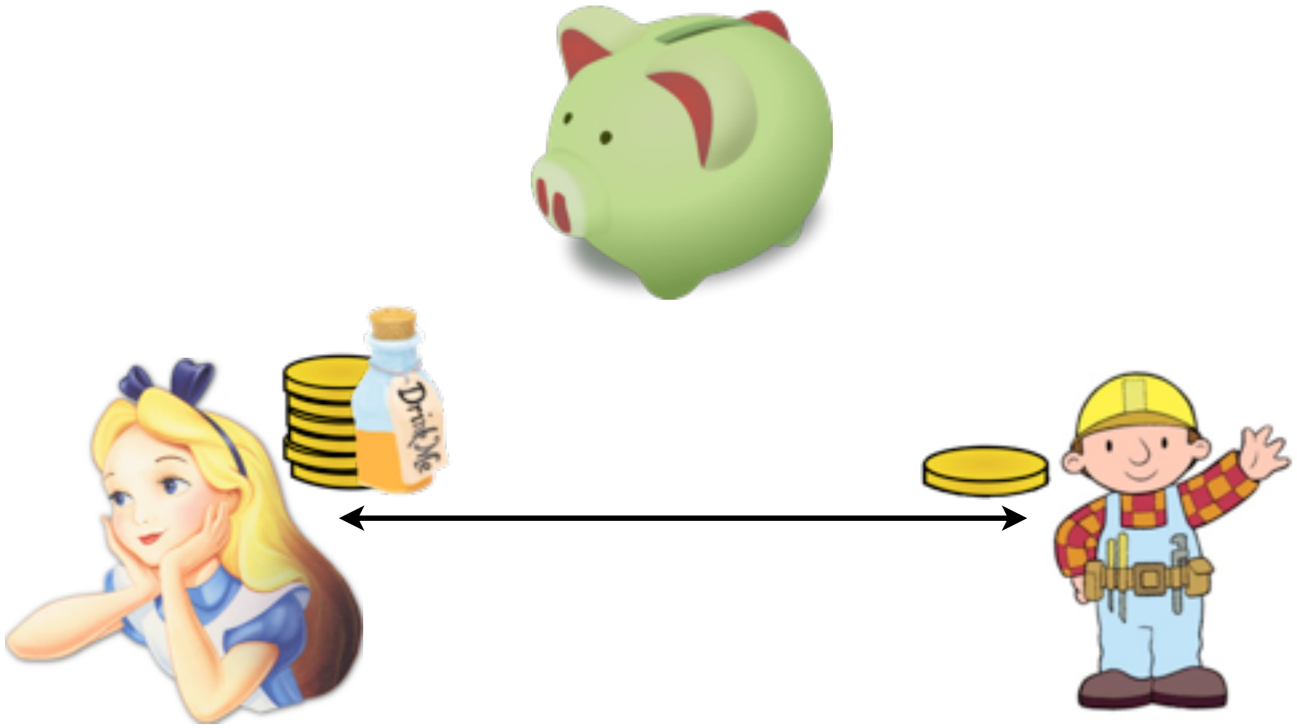

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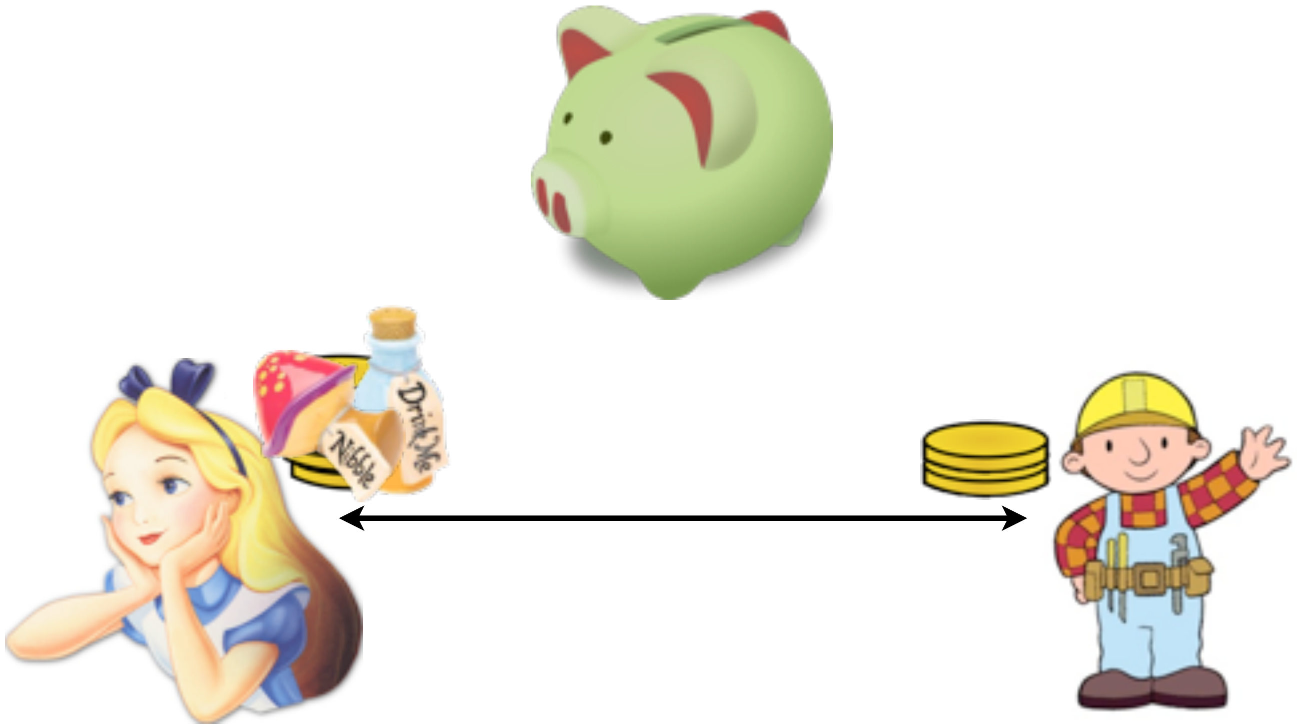

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Nibble
Drink Me

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Buy: Alice gives Bob coin in exchange for her purchase

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Deposit: Bob deposits these coins with the bank

Untraceability: Bank cannot trace the deposited coins back to Alice

CashLib: integrating e-cash into a P2P system

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Operations:

Actors:

How e-cash can improve P2P interactions:

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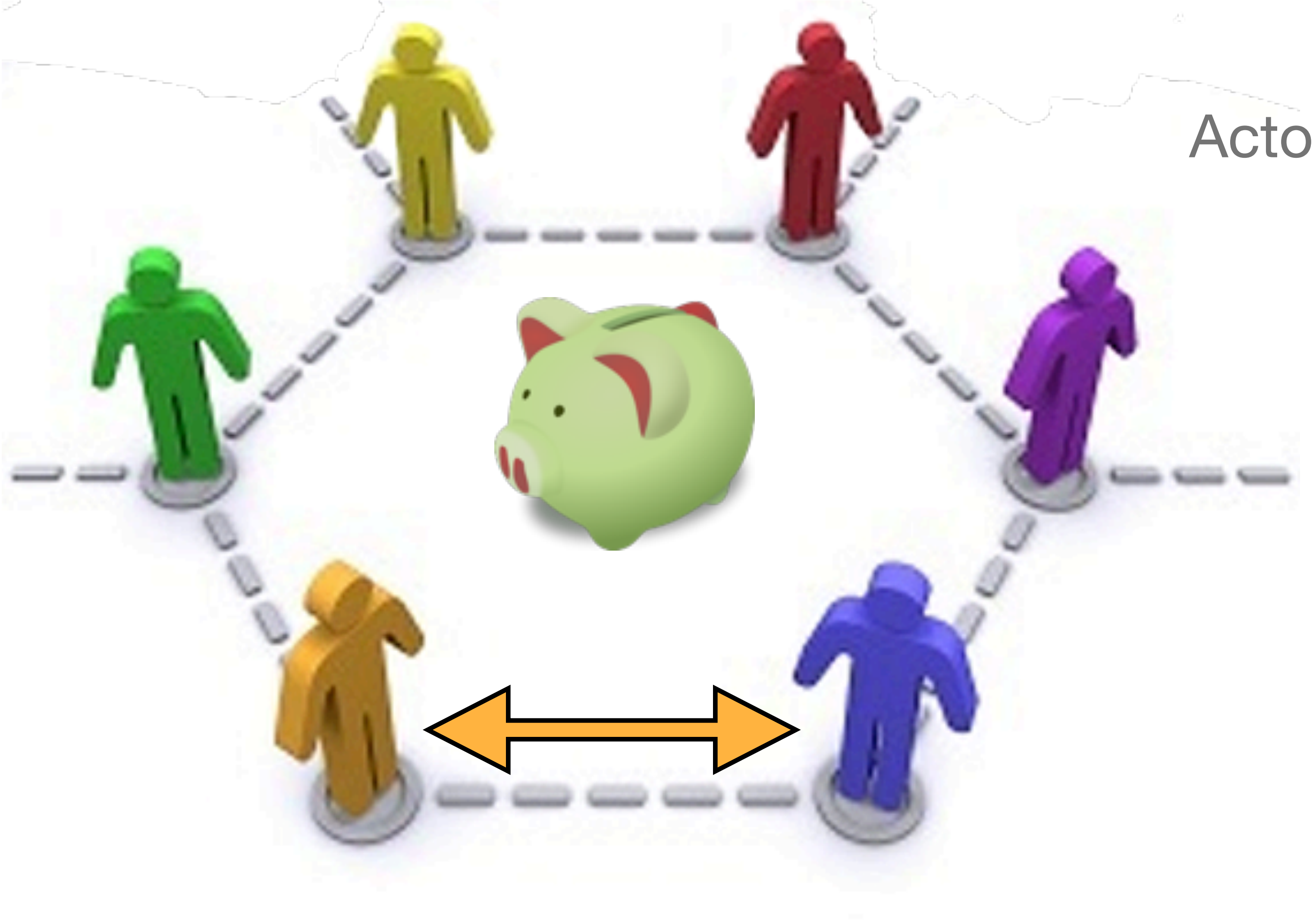

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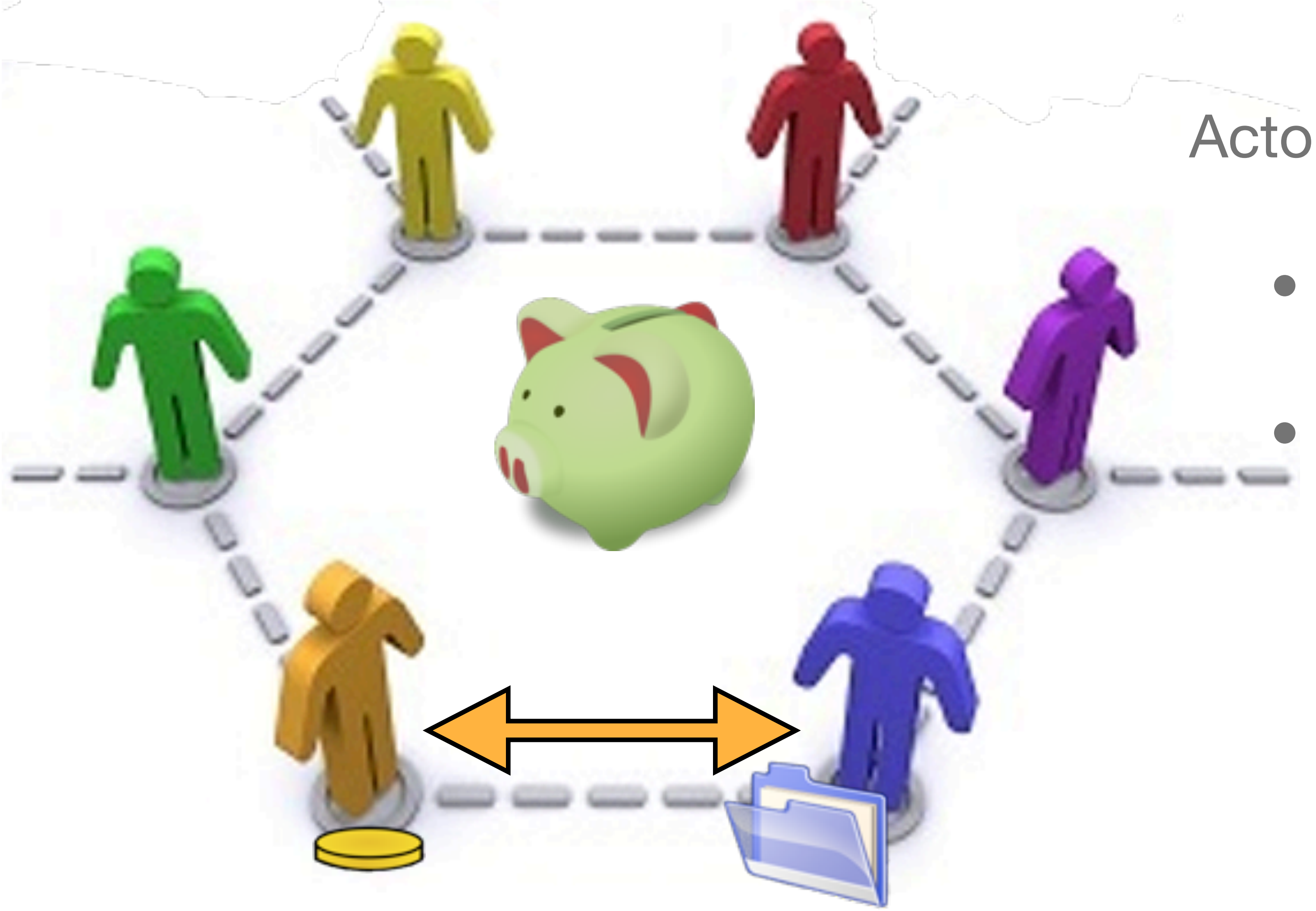

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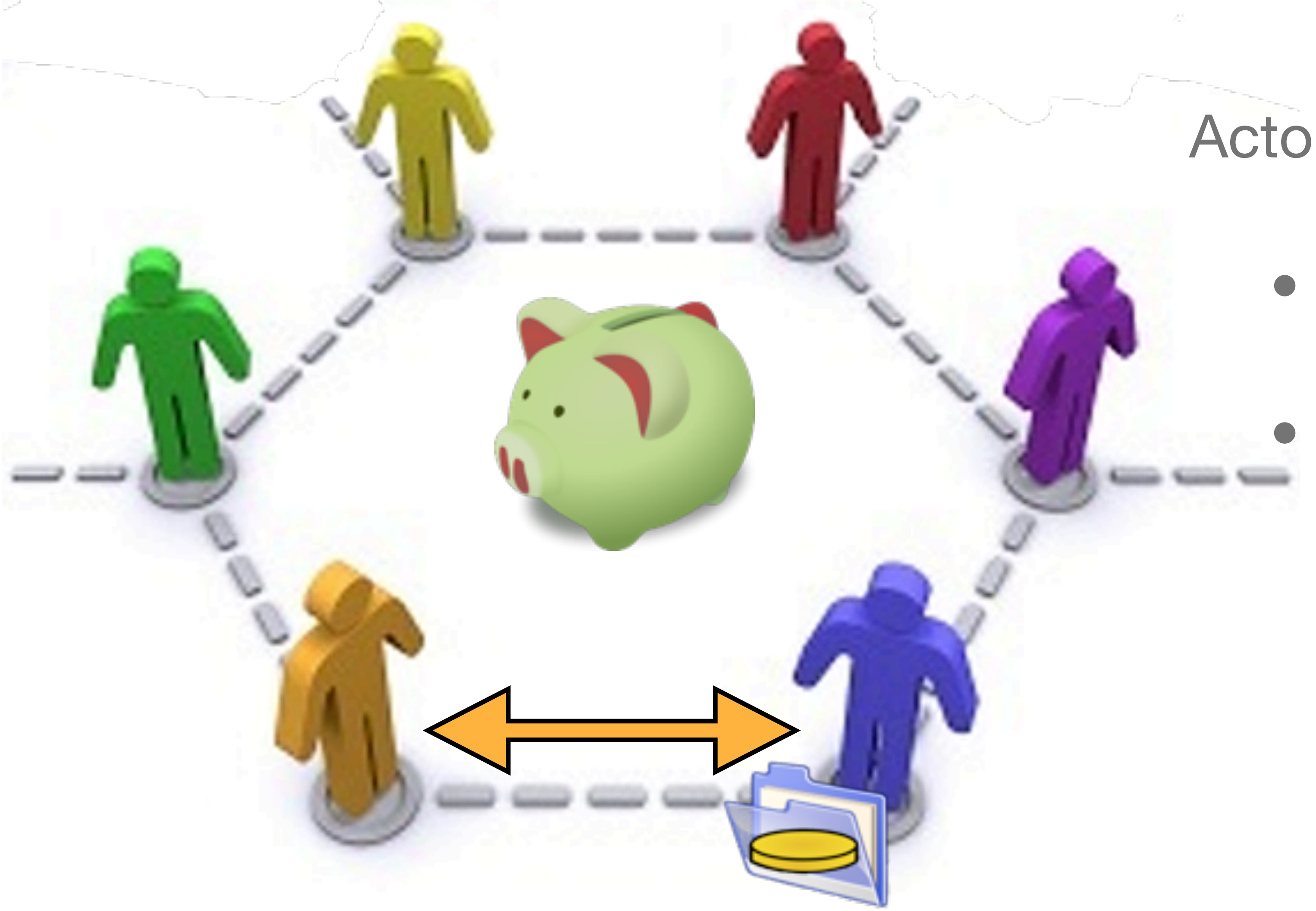

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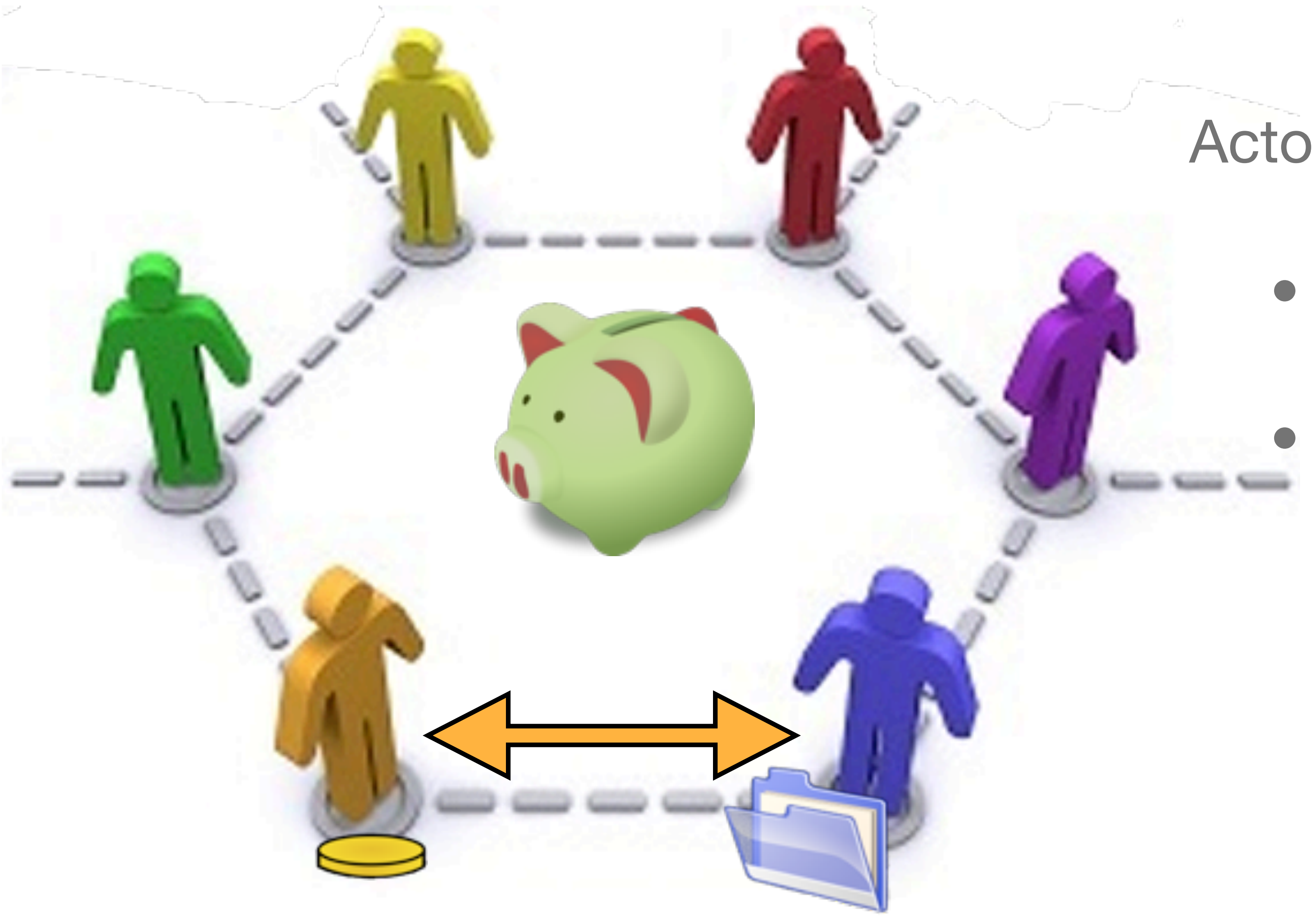

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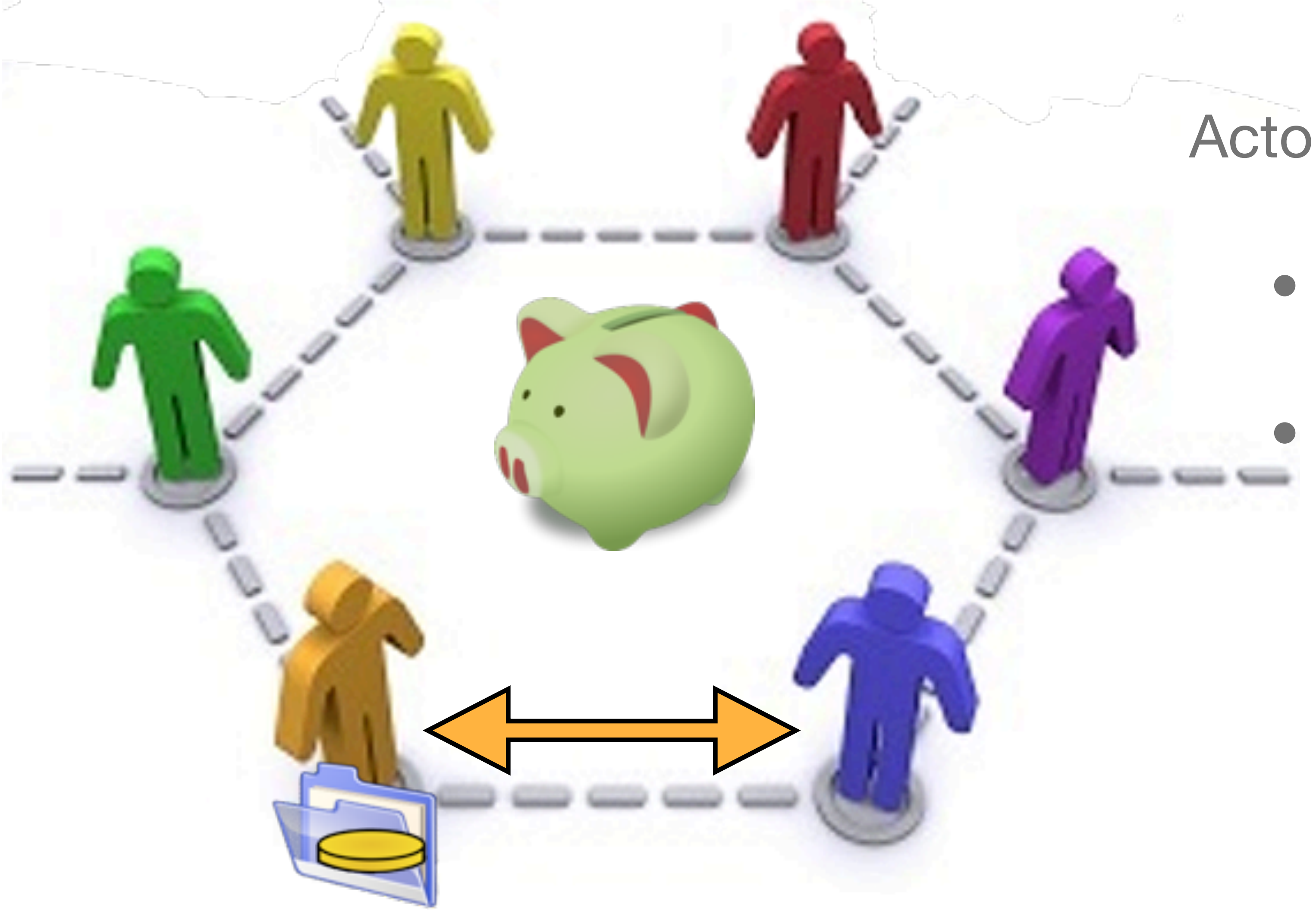

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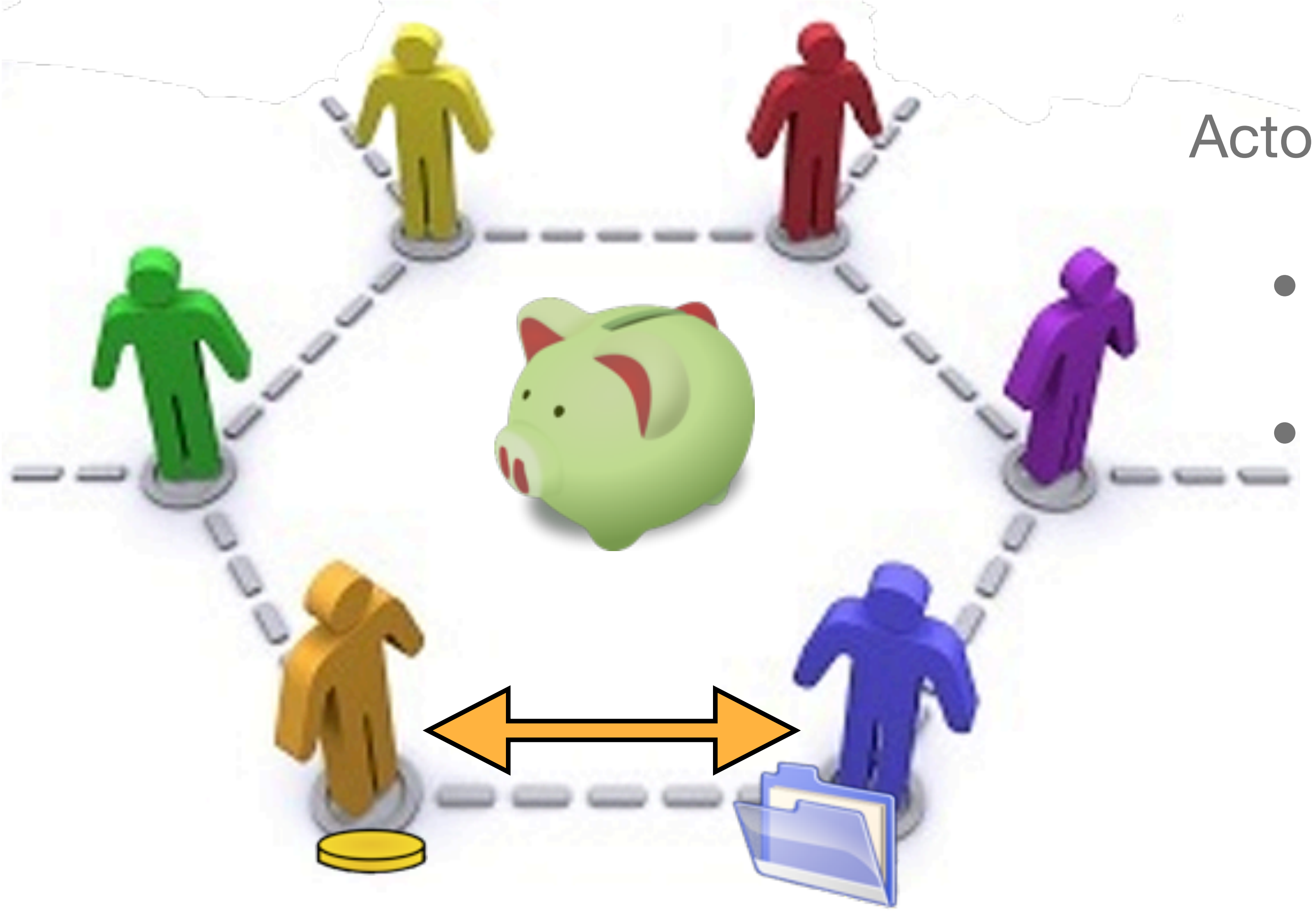

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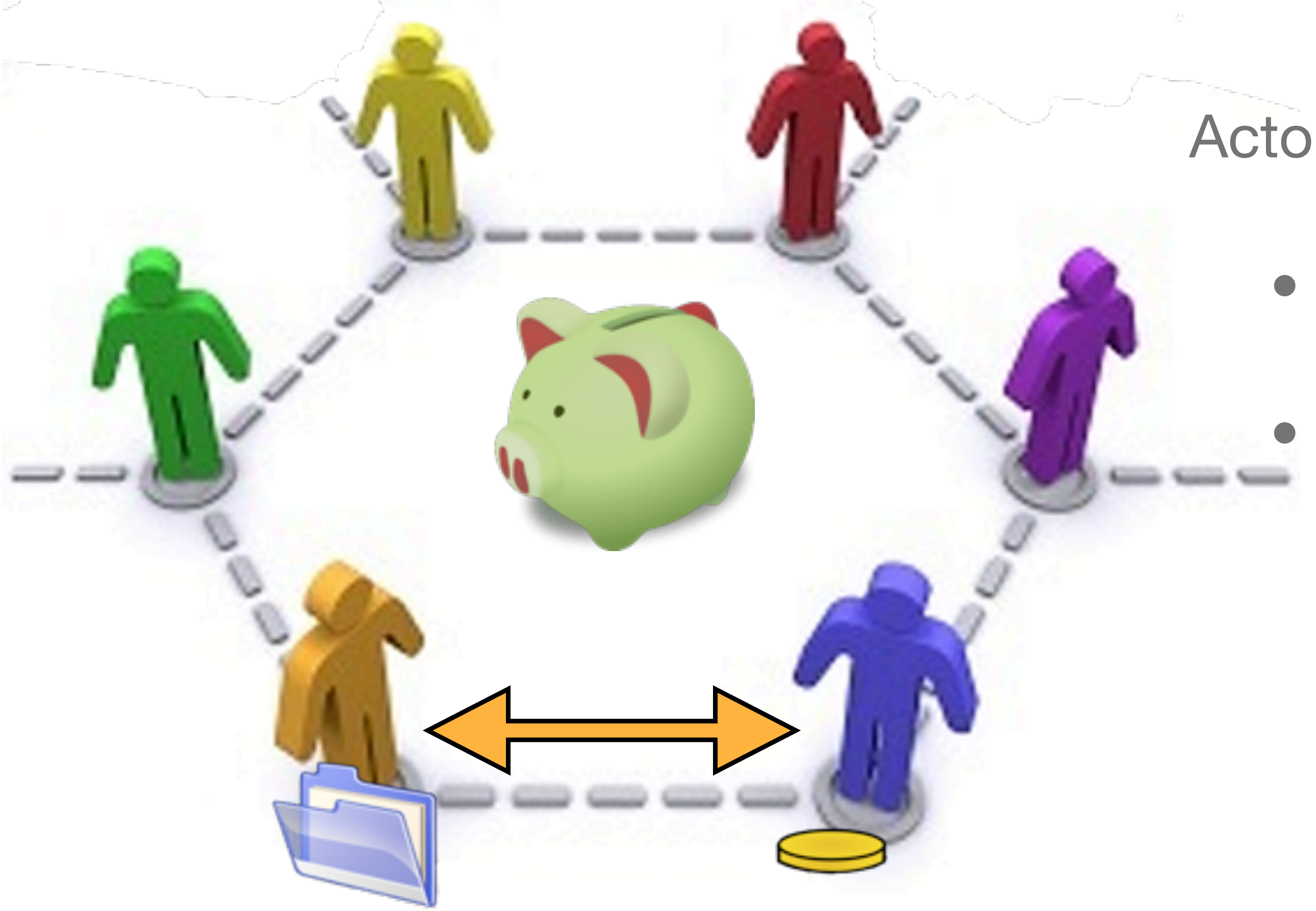

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How e-cash can improve P2P interactions:

- Guarantees fair exchange [BCE+07,KL10] between peers

CashLib: integrating e-cash into a P2P system

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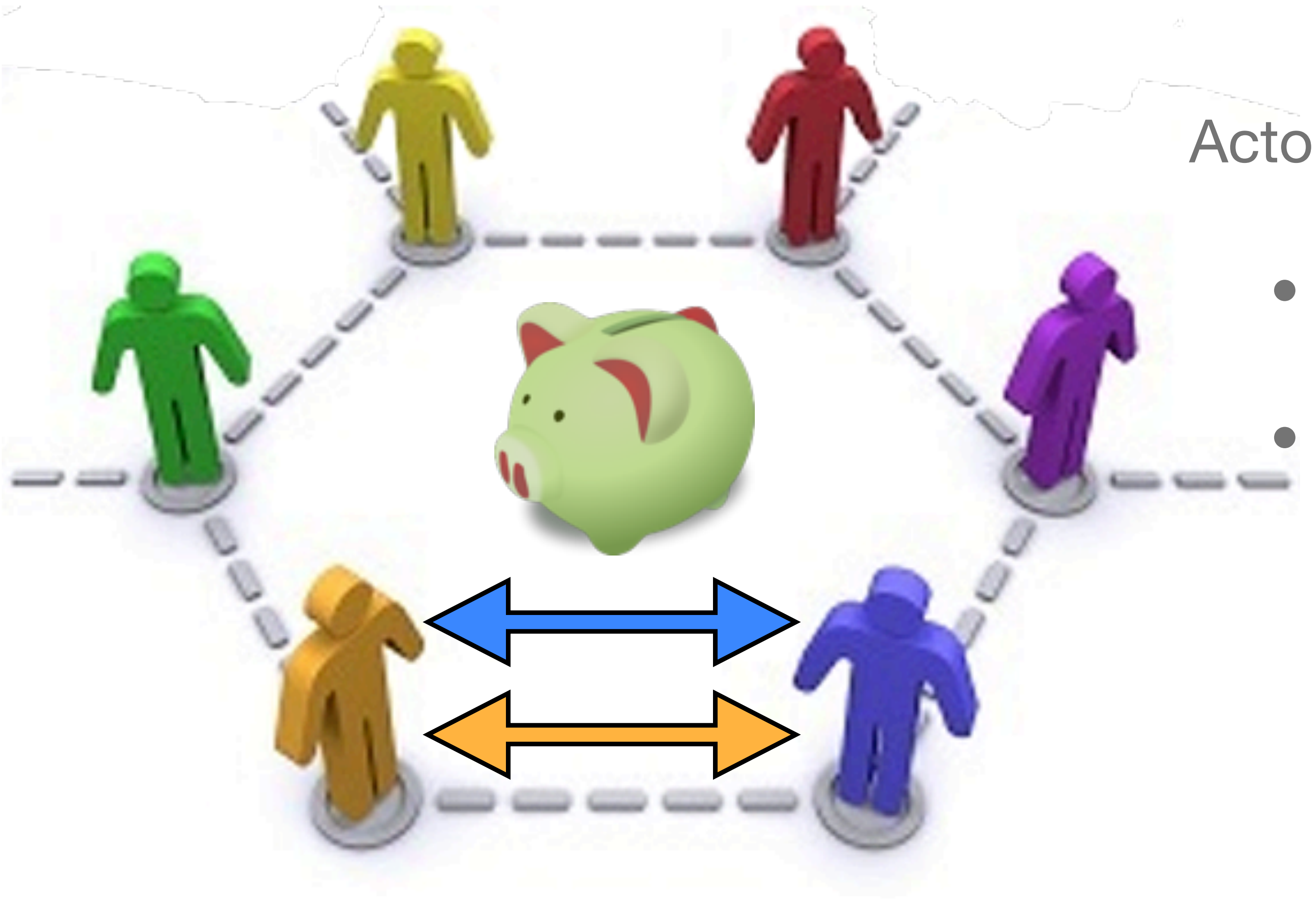

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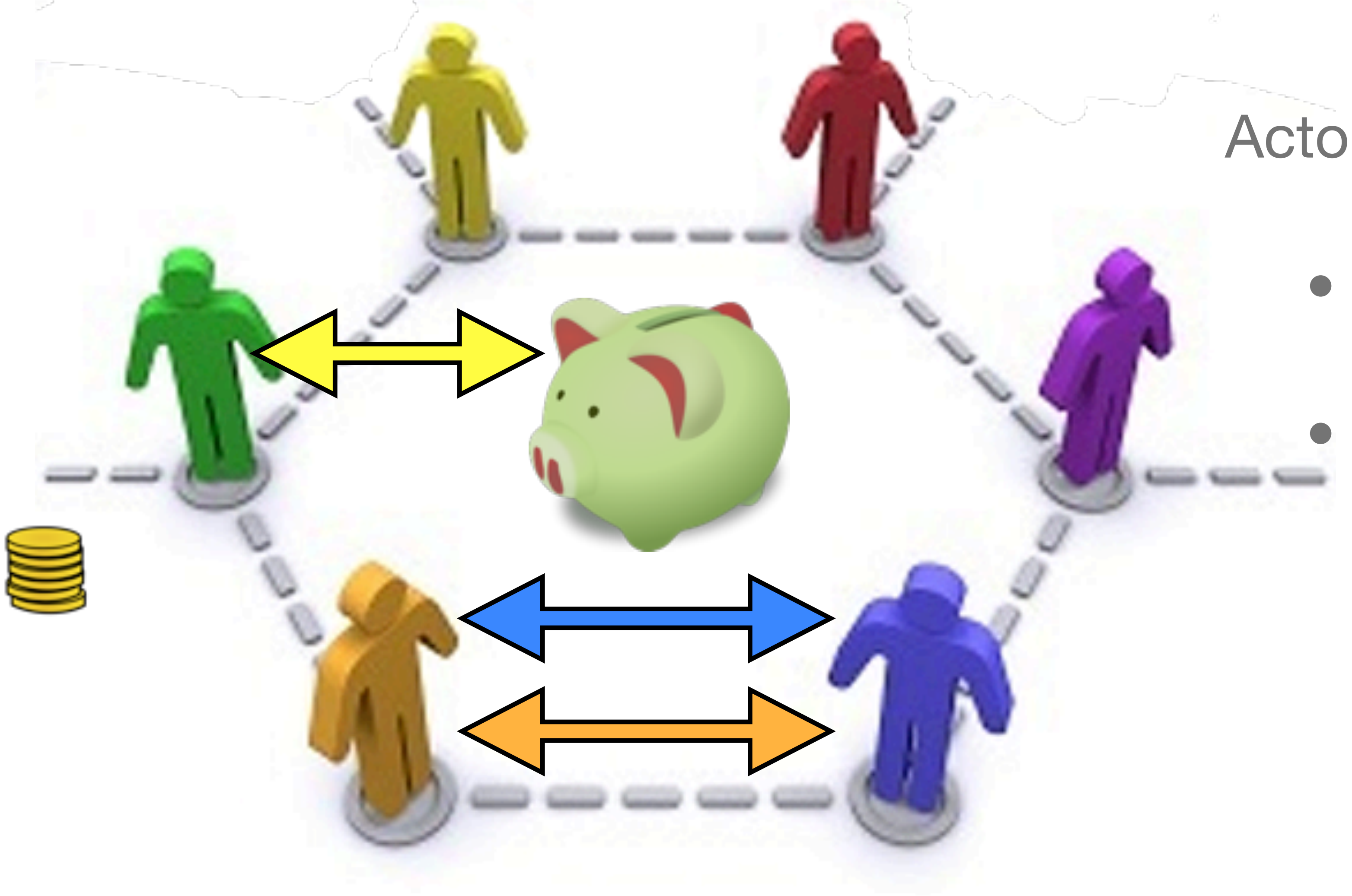

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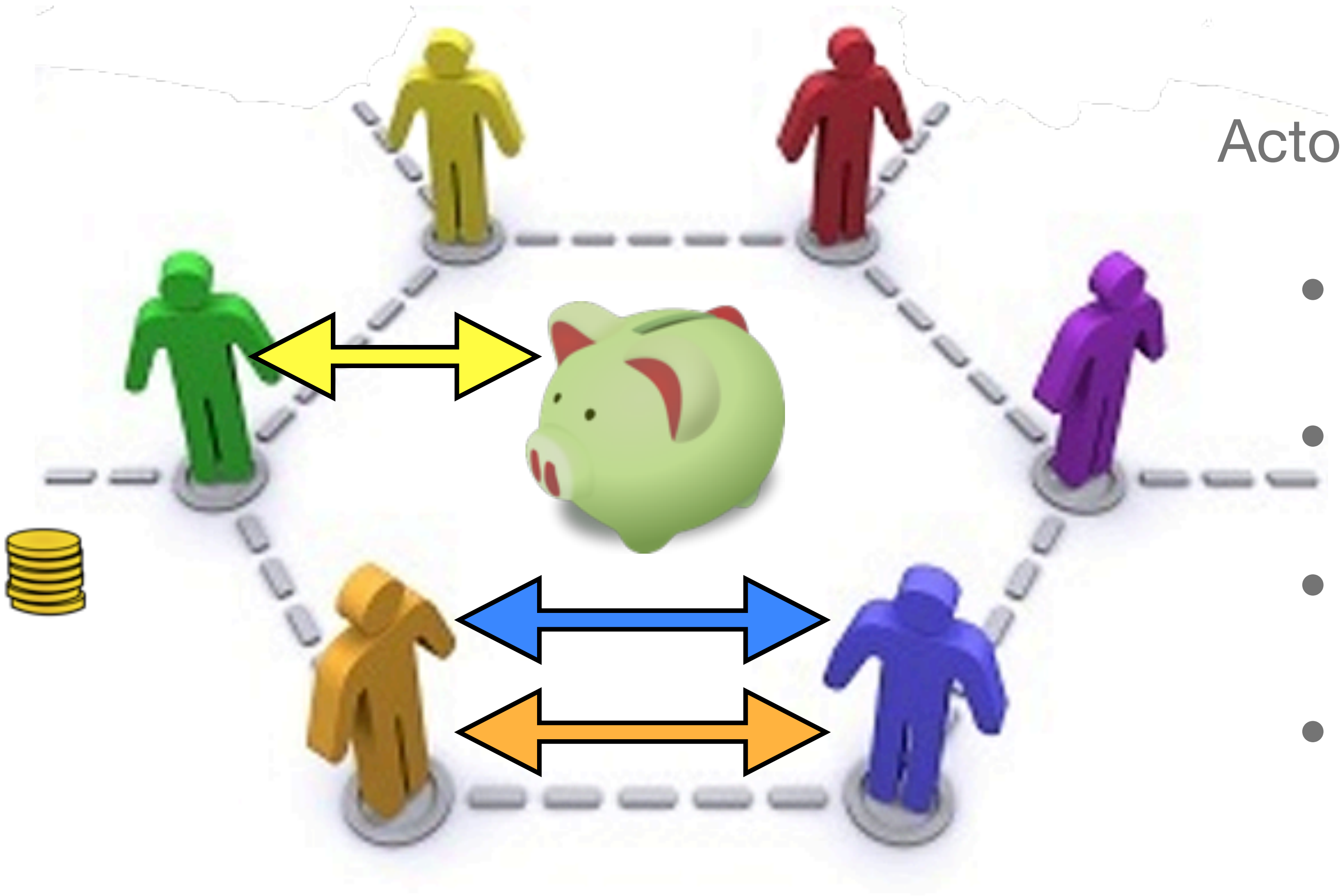

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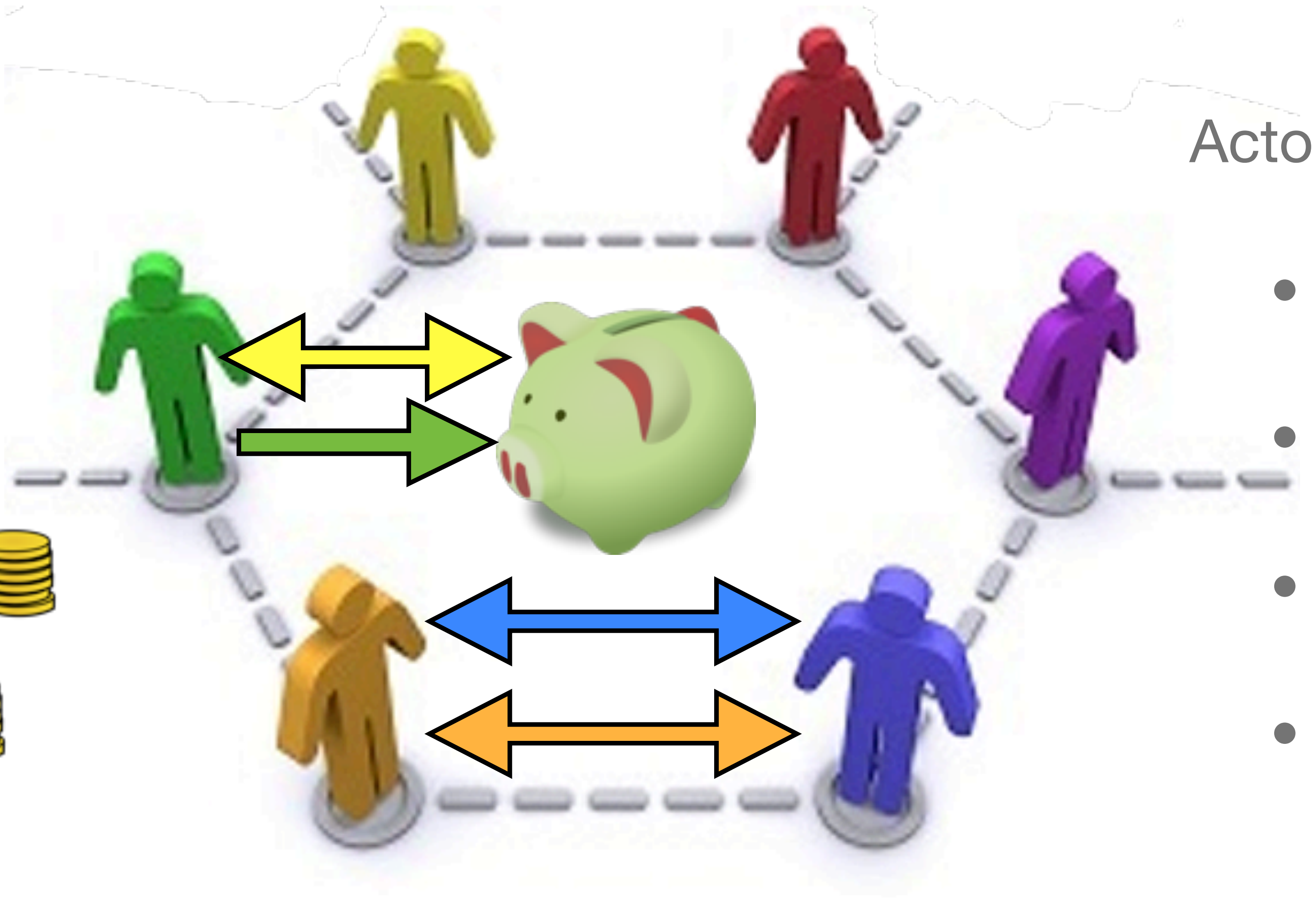

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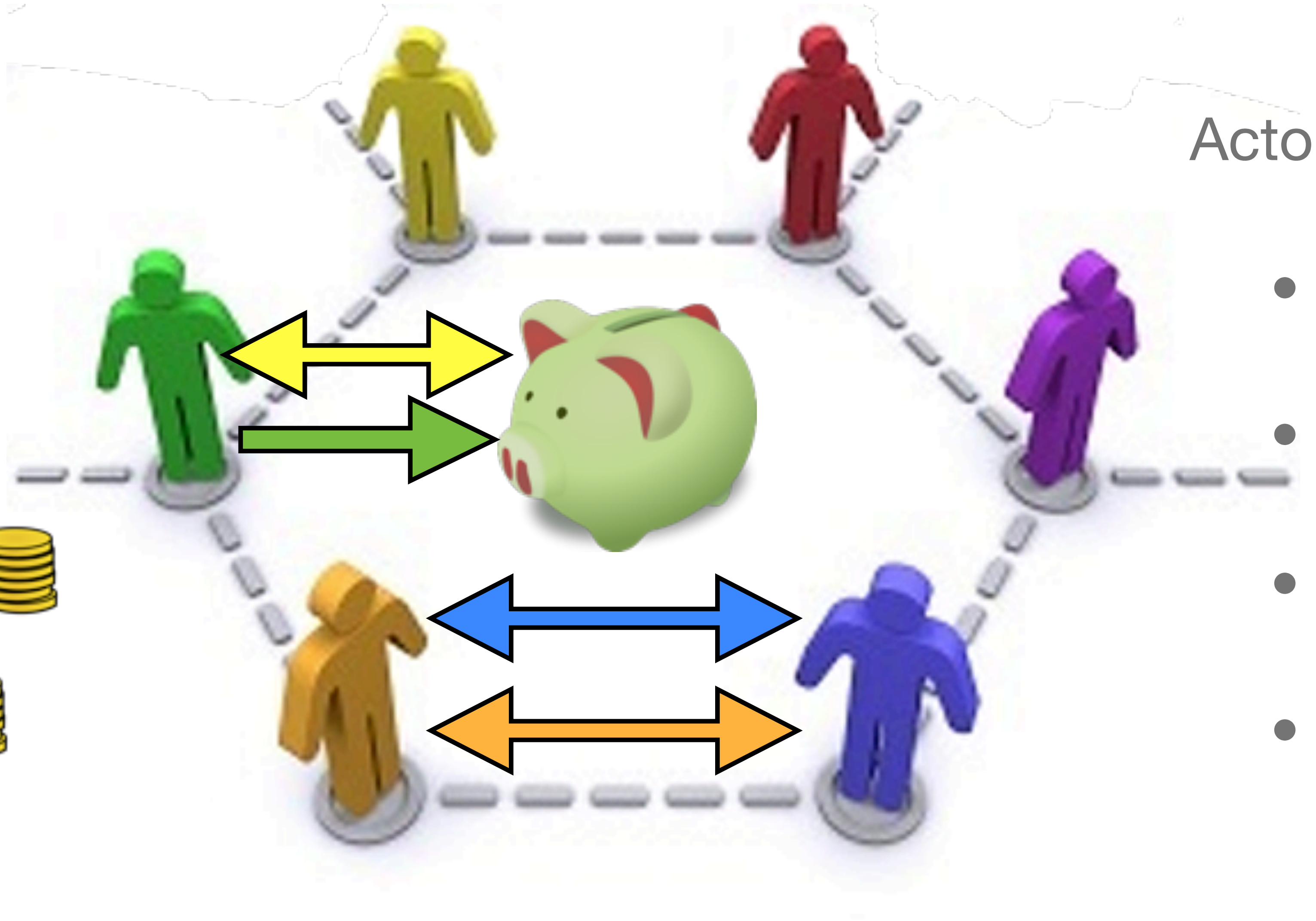

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How e-cash can improve P2P interactions:

- Guarantees fair exchange [BCE+07,KL10] between peers
- Allows bank to monitor upload/download ratio without sacrificing privacy

Related work

Related work

So what aren’t we doing?

Related work

So what aren't we doing?

- Aren't guaranteeing anything about the quality of the proofs

  You give us a bad (e.g., not sound) proof, get a bad proof back

  Checking soundness is well studied by others [CACE]

Related work

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- As application of zero knowledge, provide library only for e-cash

  Idemix project [CH02, BBC+09] provides anonymous credentials

In summary...

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  - Demonstrated efficiency and usability
- Wrote library to make programmer’s job easier
- All source code and documentation available freely online:
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Any questions?

Zero knowledge proof types

- What types of proofs do we support?
    - Proof of discrete log representation (DLR): given c, prove `c = g^x*h^r`
    - Equality of DLR: given c and d, prove `c = g^x*h^r` and `d = g^x*h^s`
    - Multiplication: prove `x = y*z` for secret values x, y, z
    - Range: for secret x and public lo, hi, prove `lo <= x < hi`