Flexible Models for Secure Systems

Sarah Meiklejohn

A creation story

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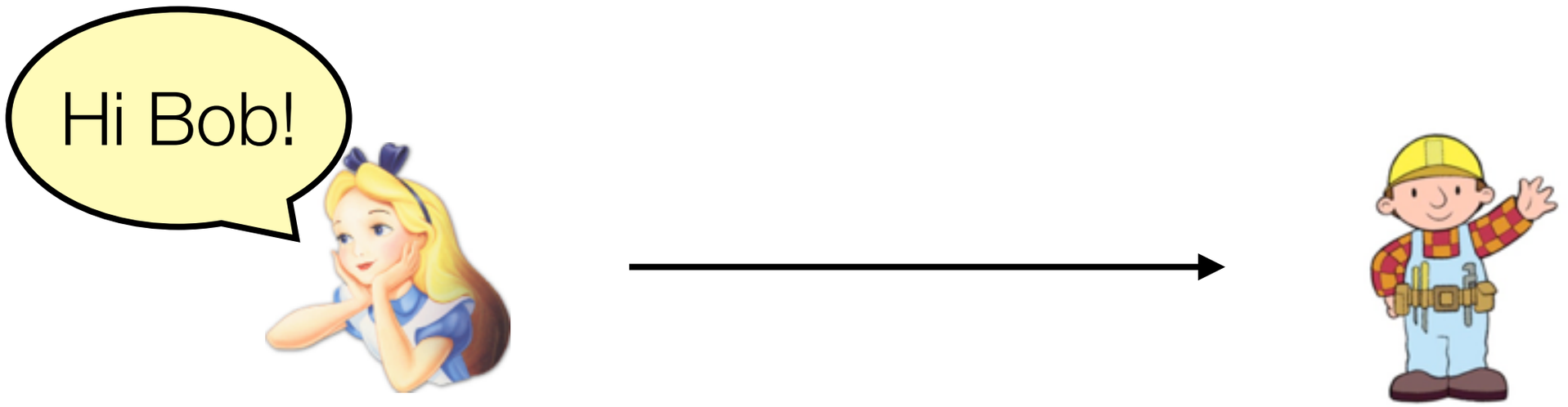

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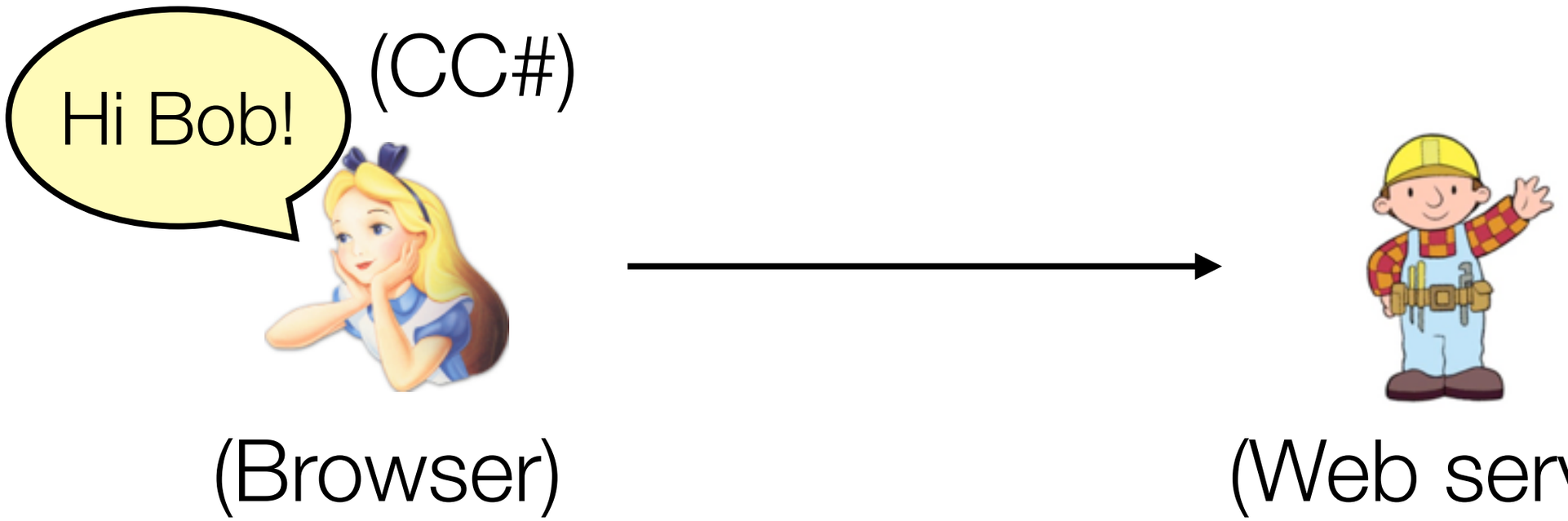

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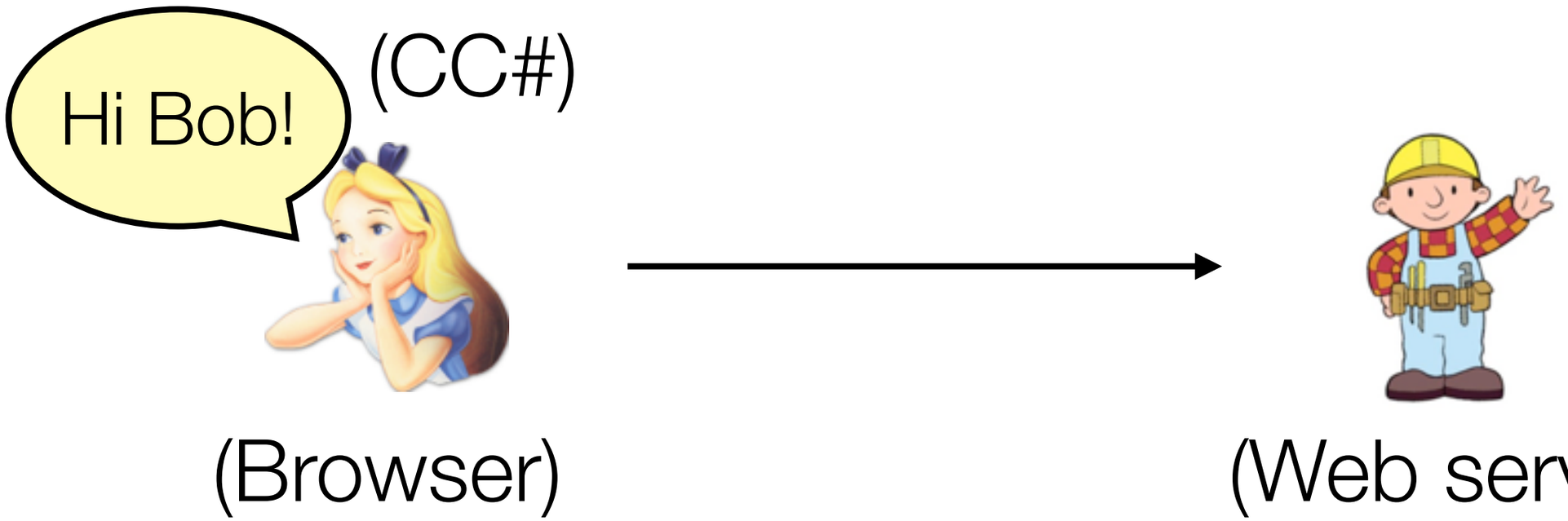

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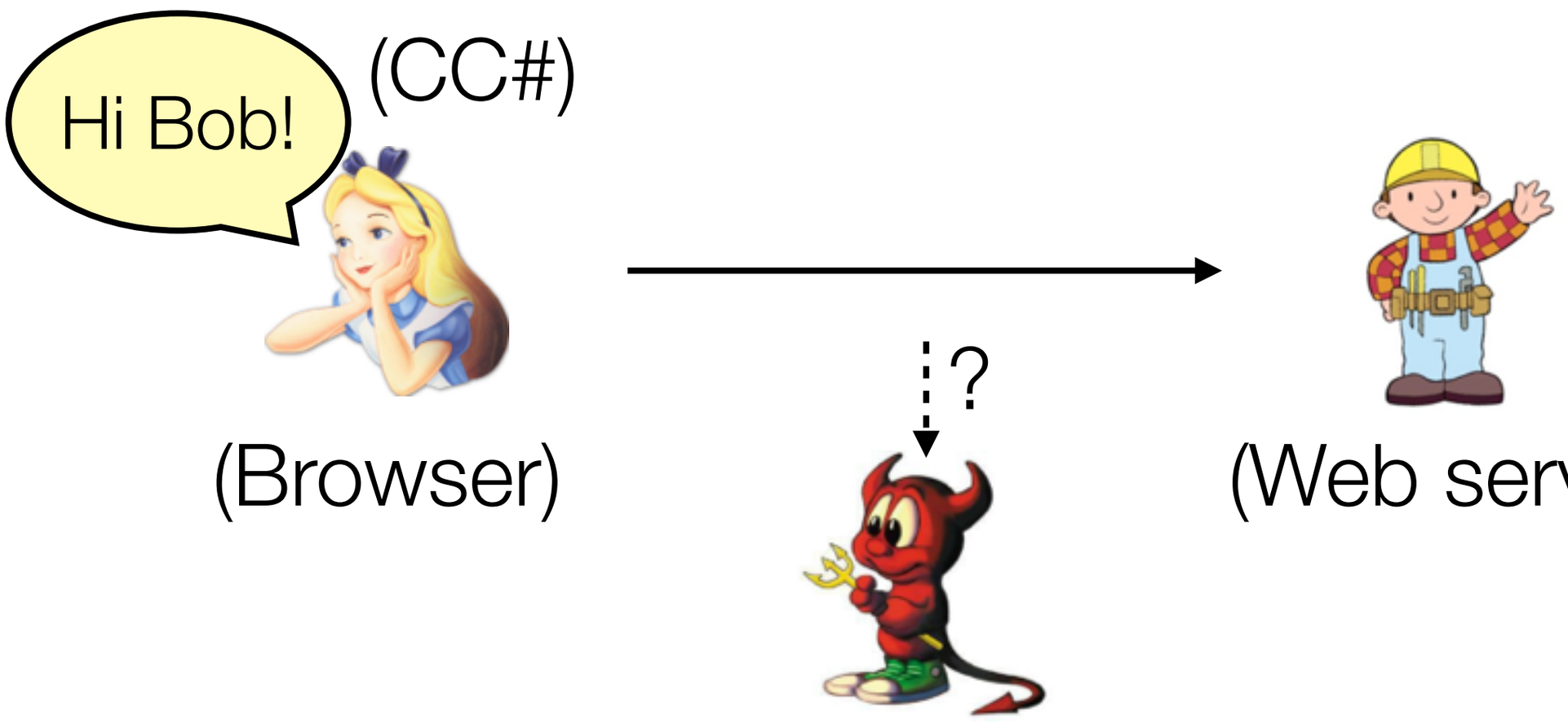

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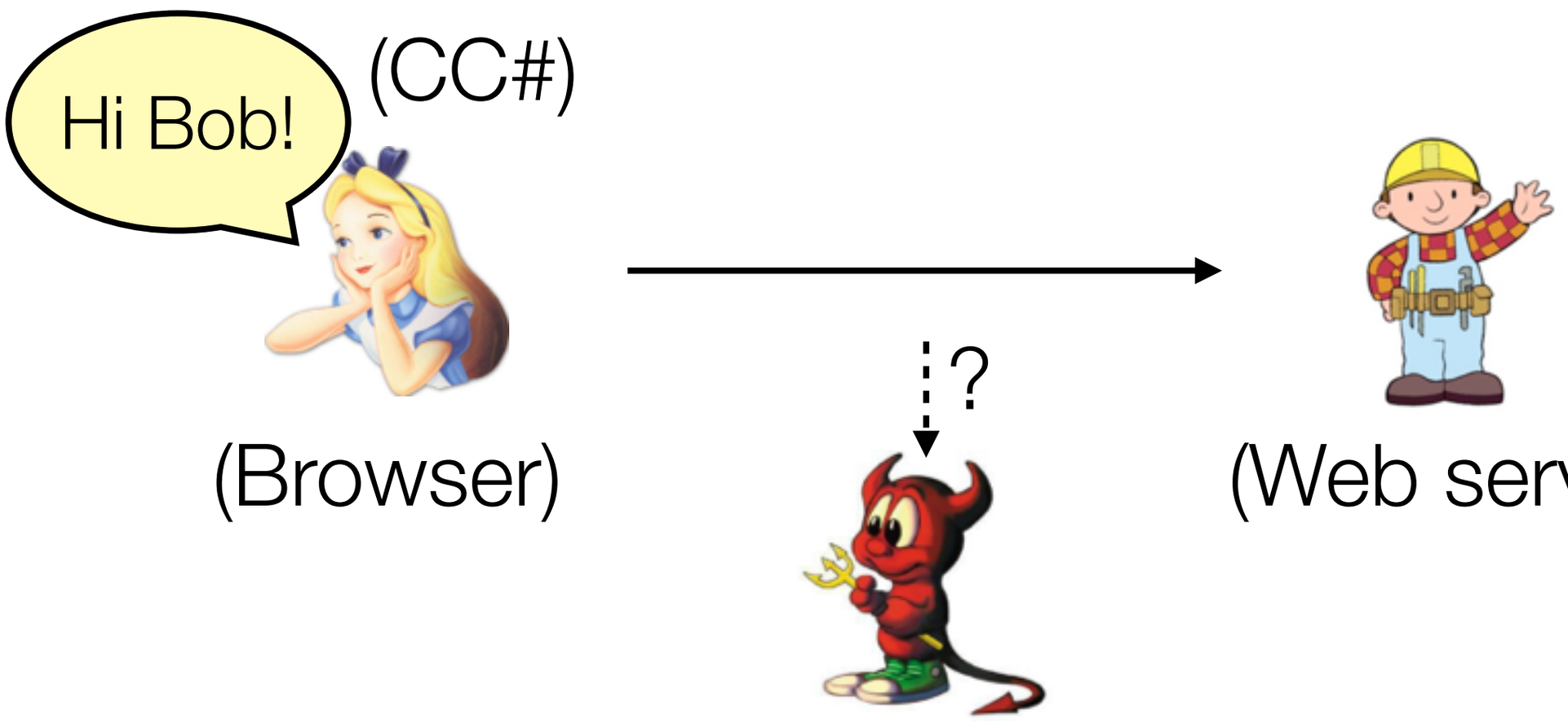

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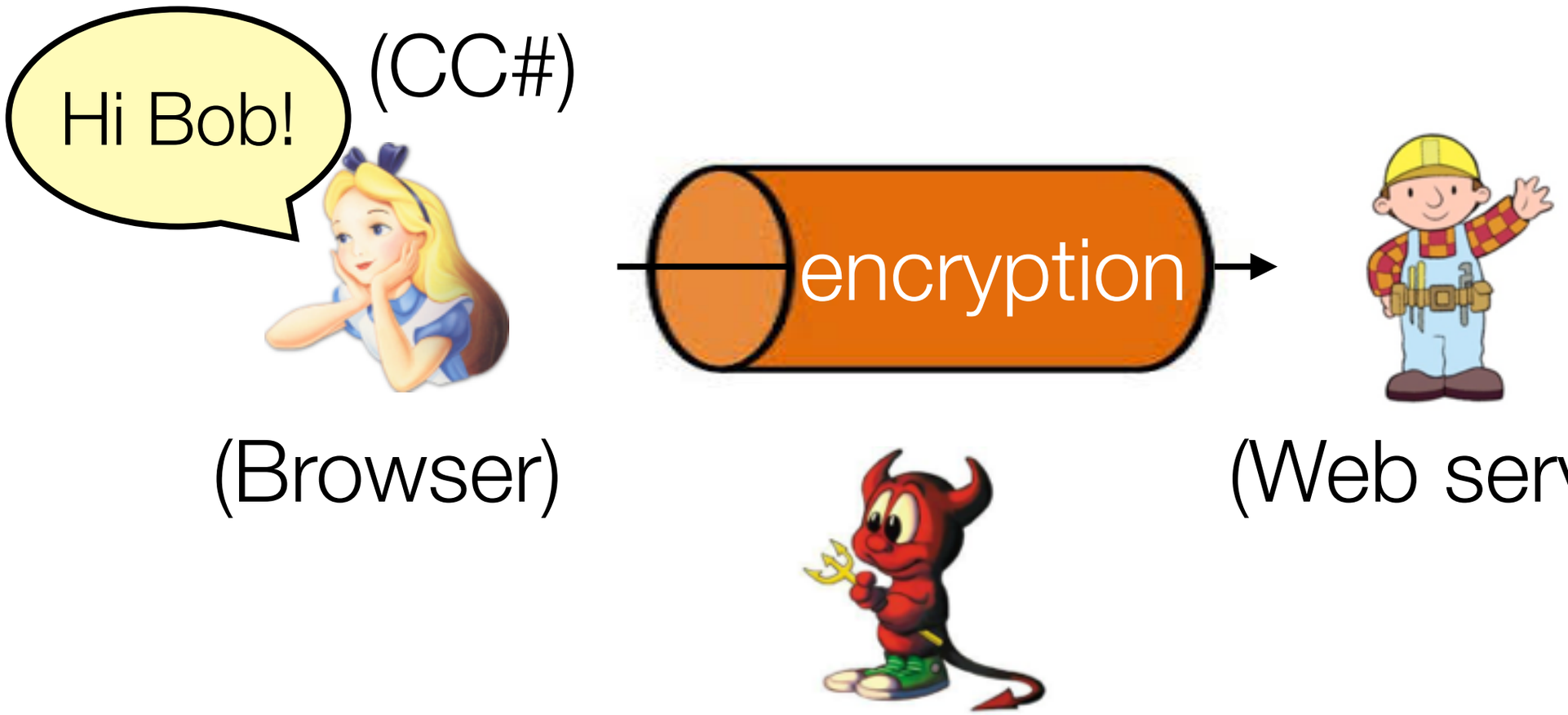

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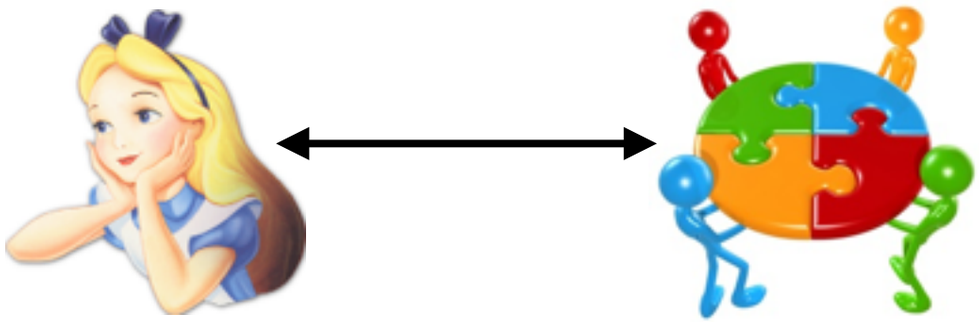

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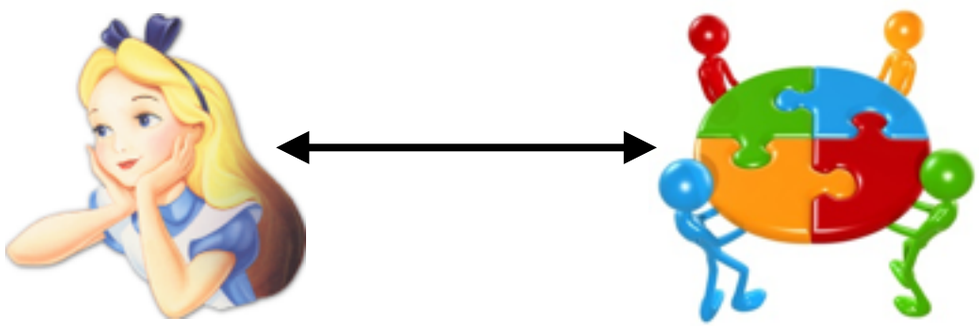

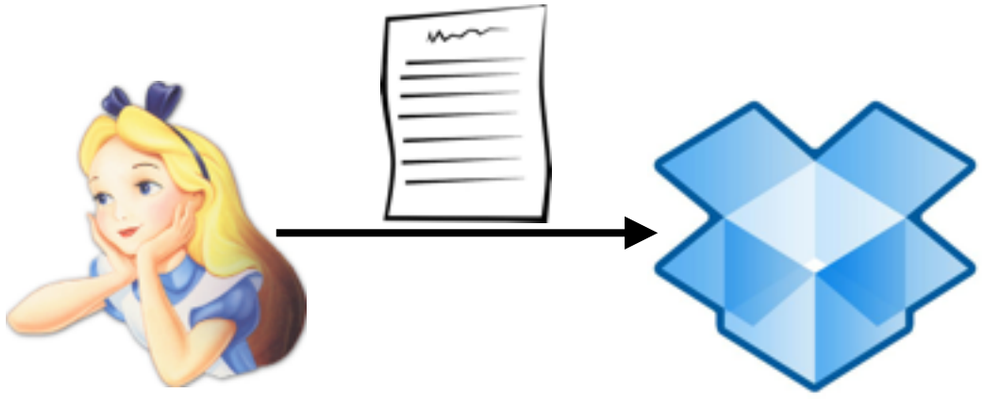

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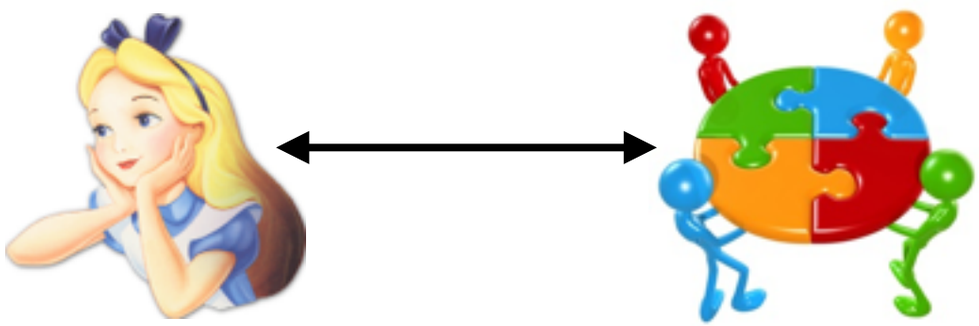

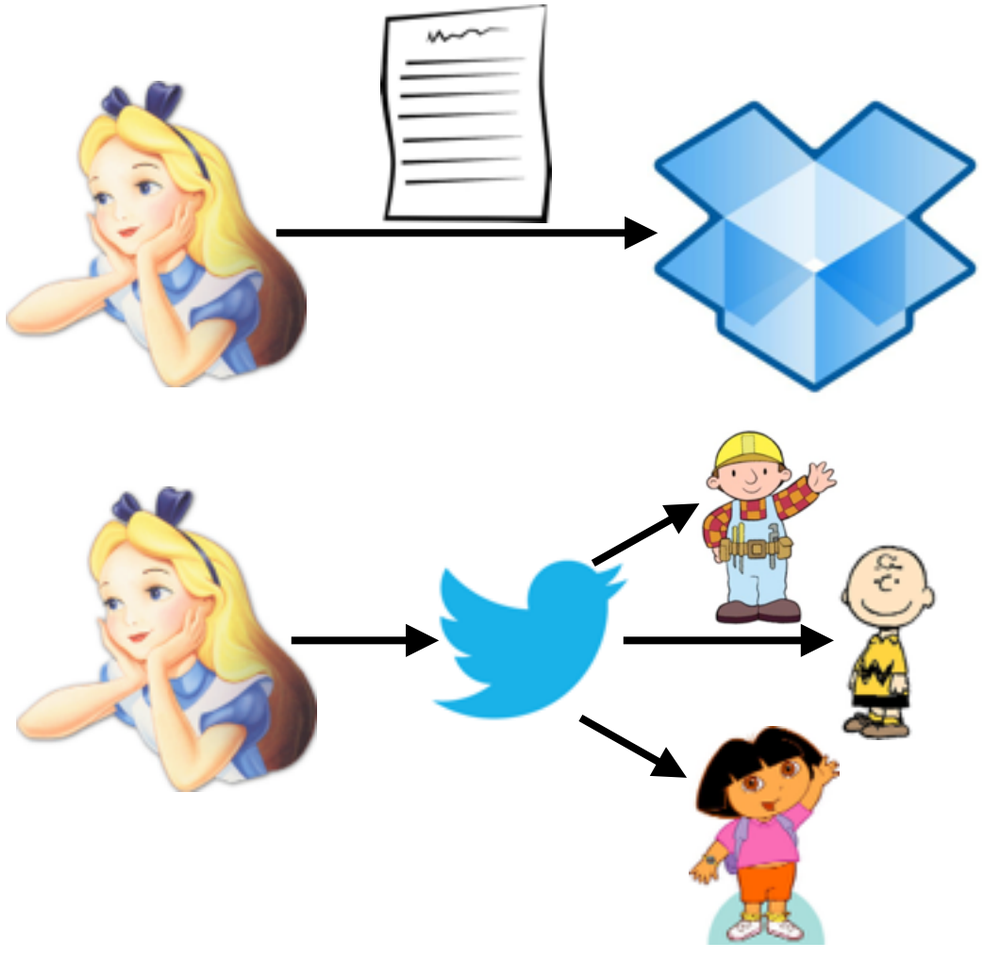

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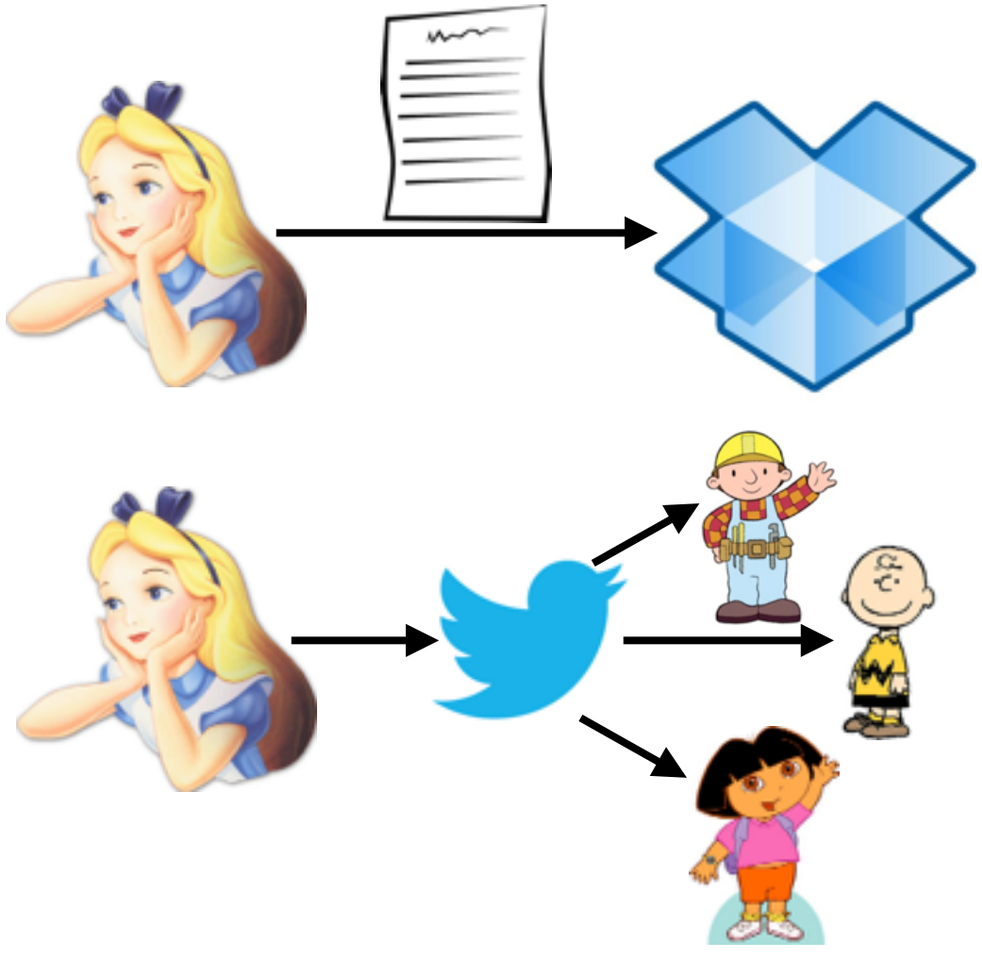

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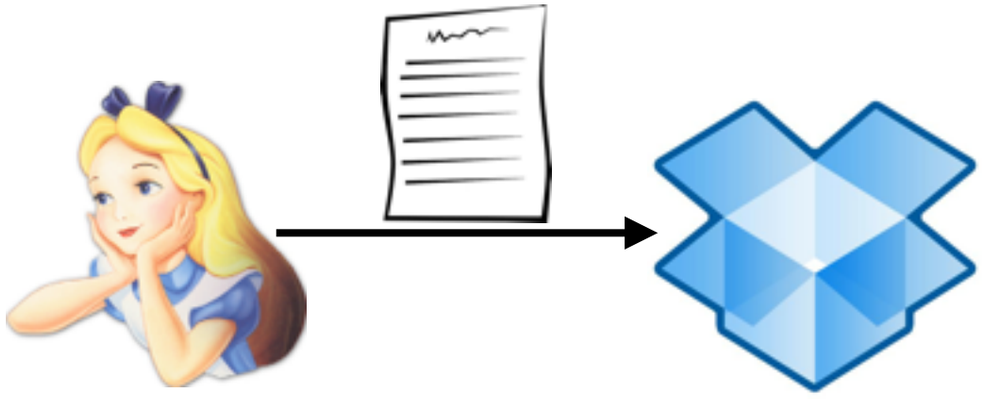

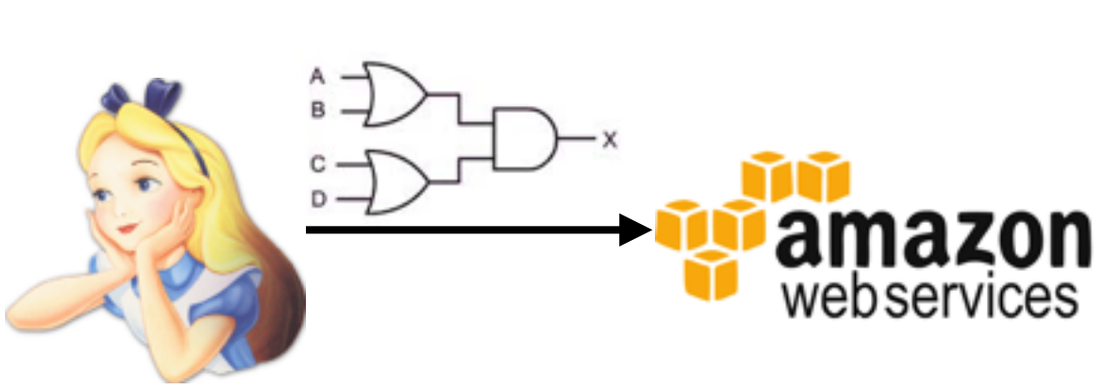

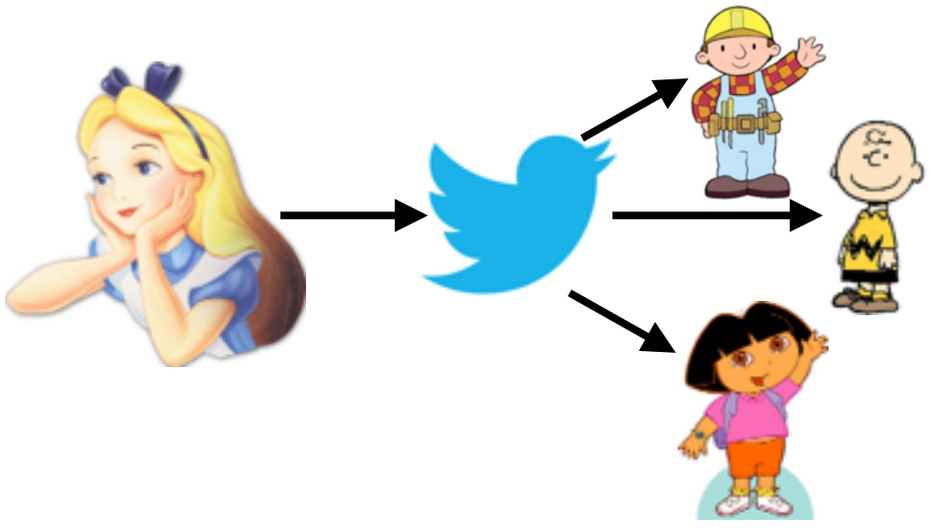

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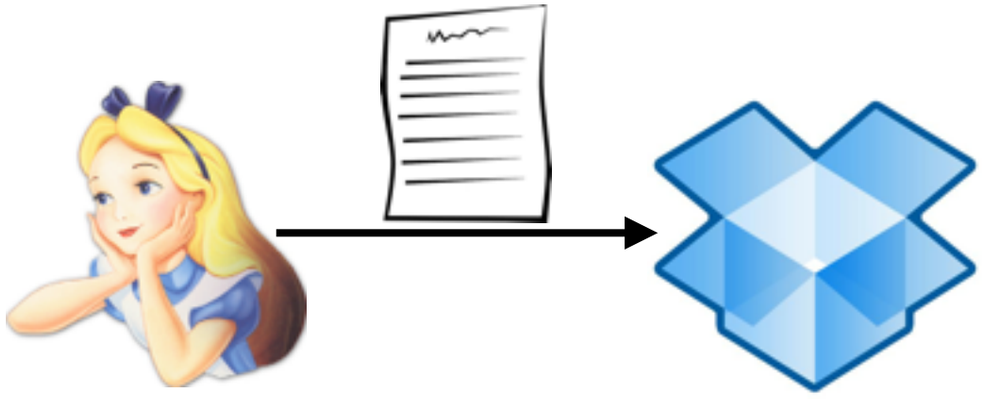

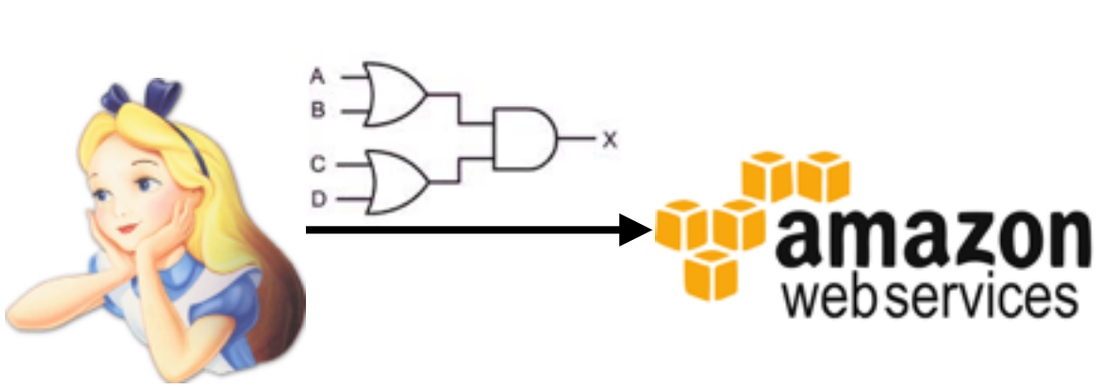

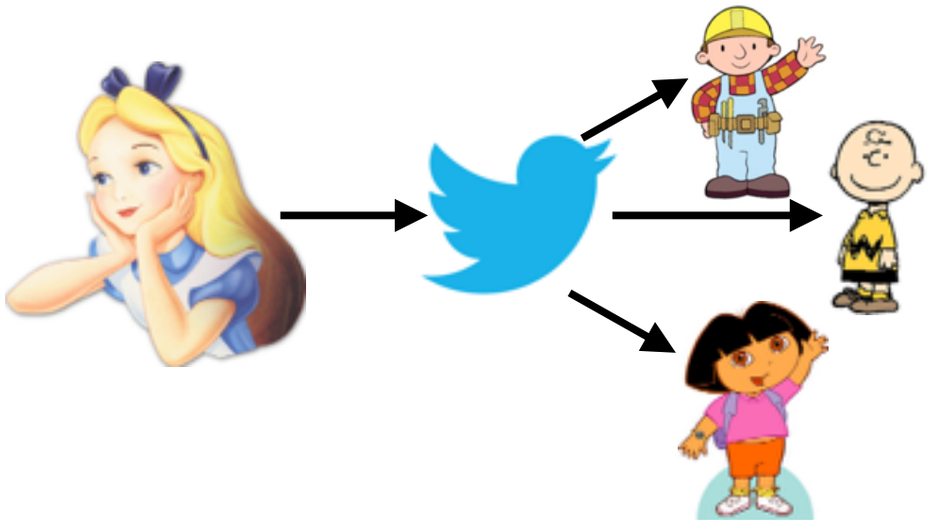

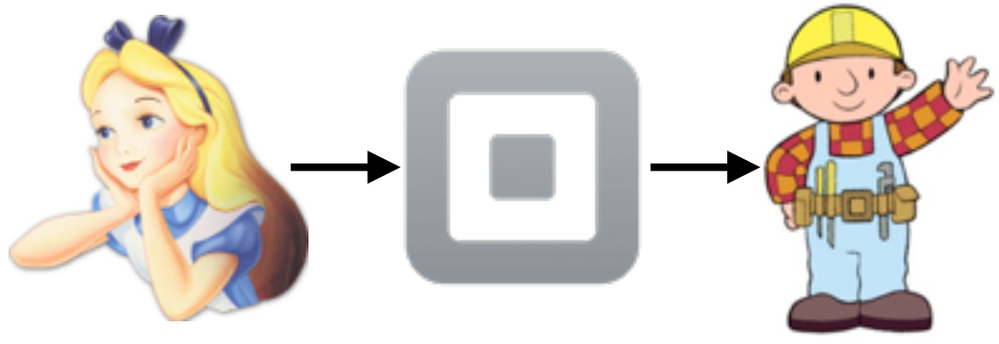

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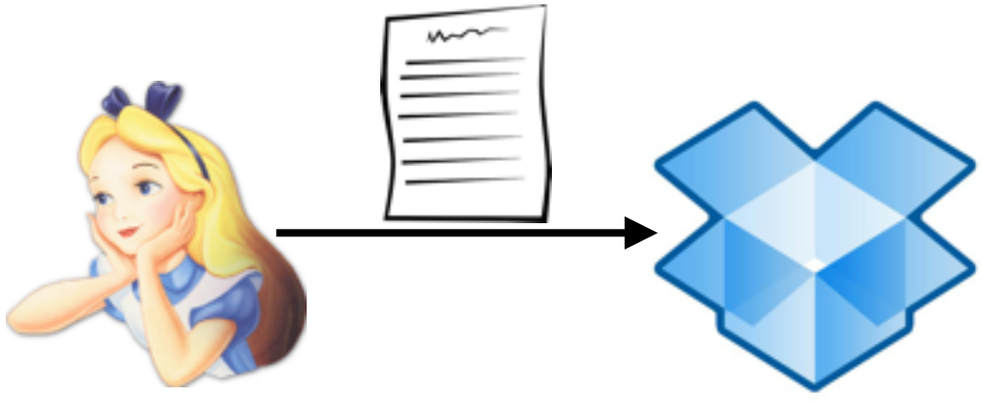

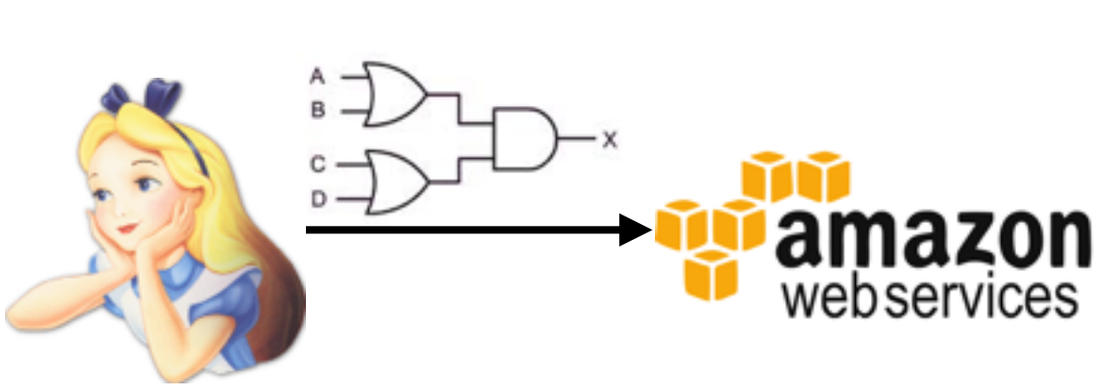

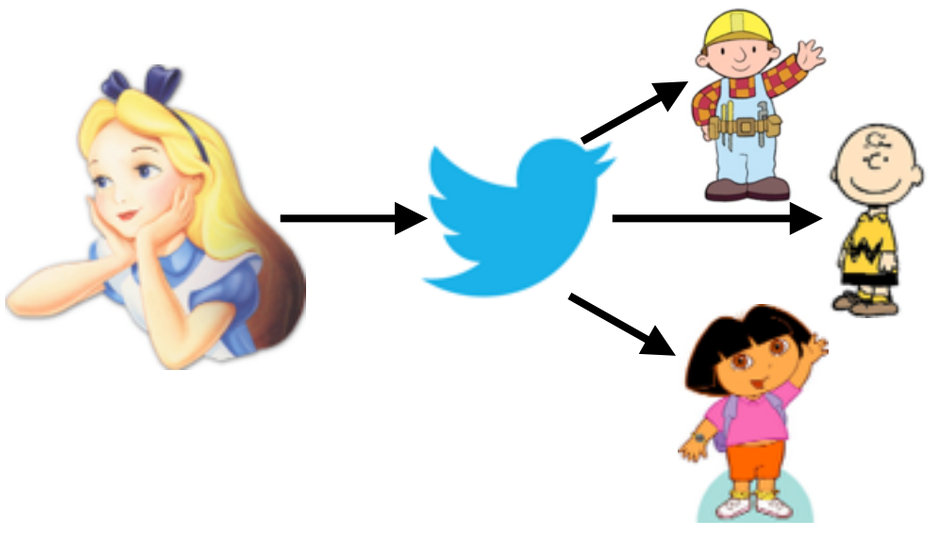

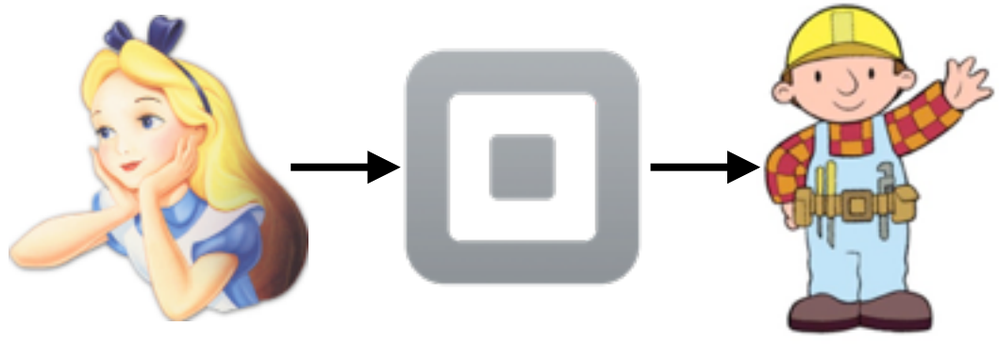

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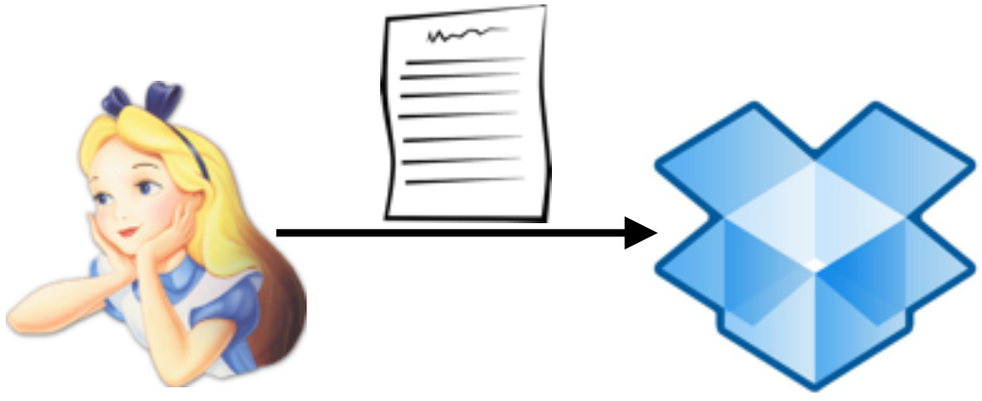

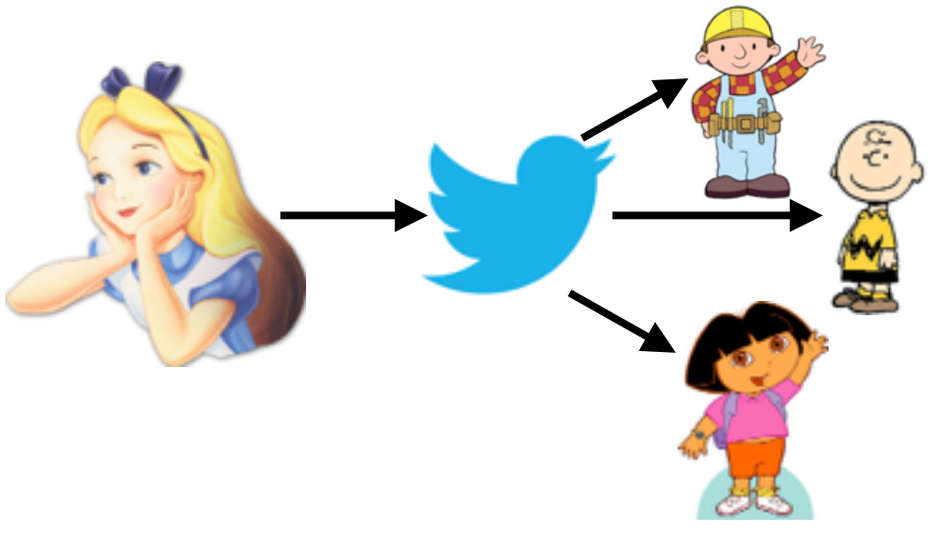

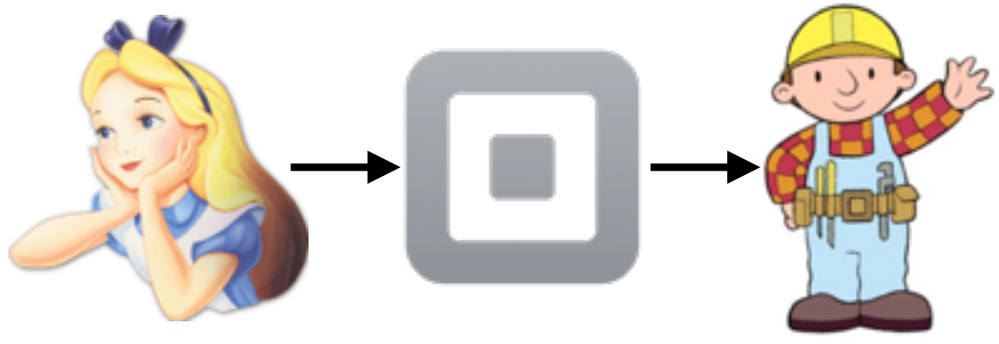

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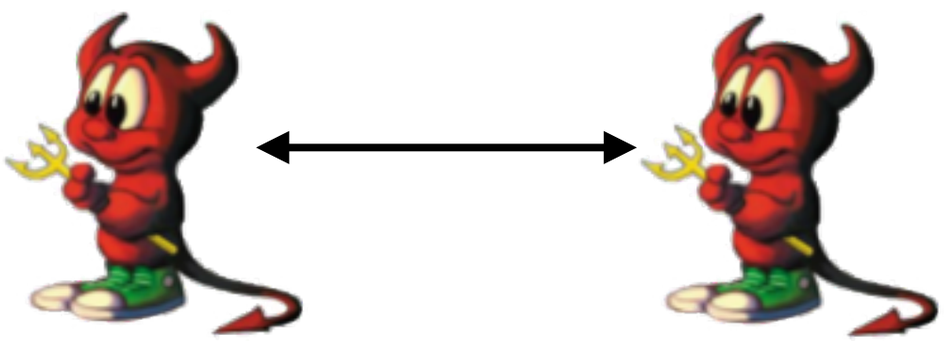

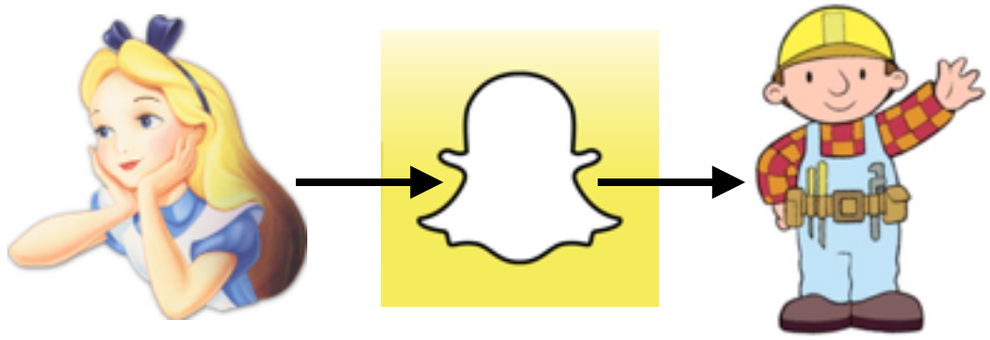

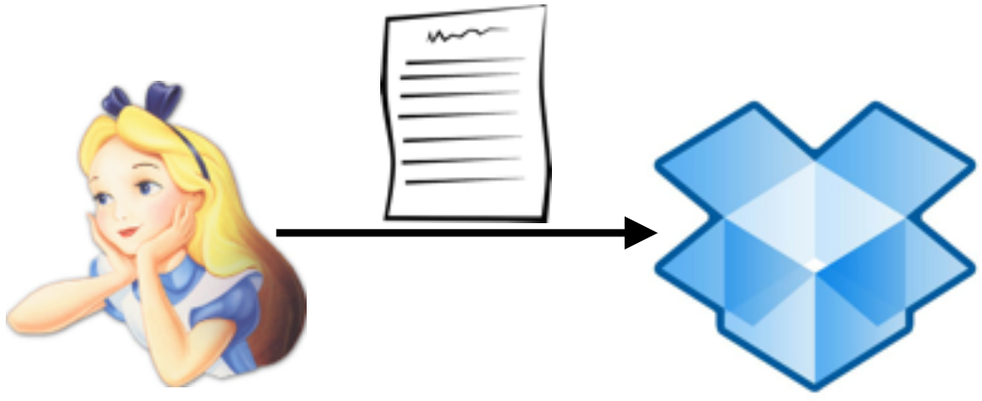

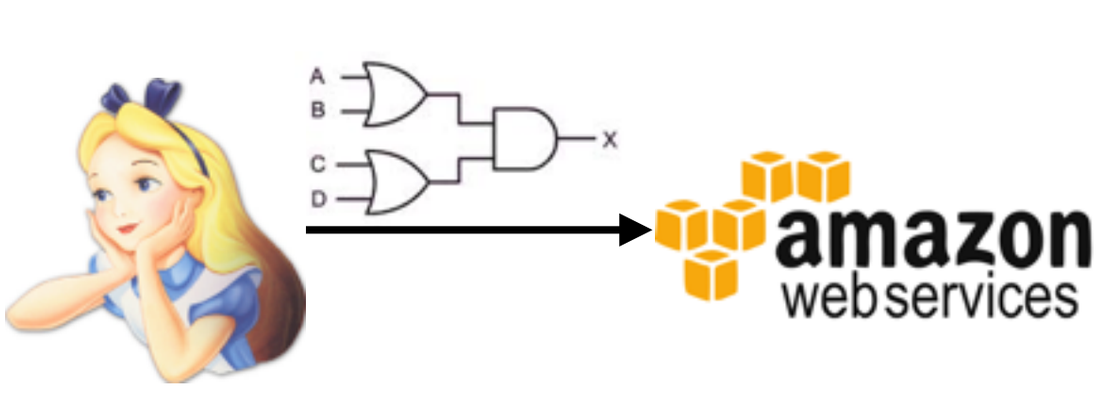

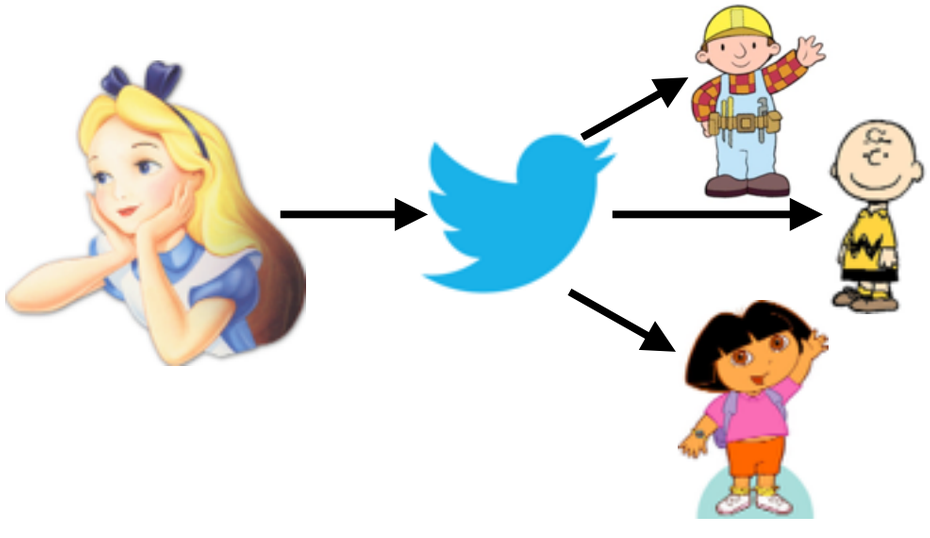

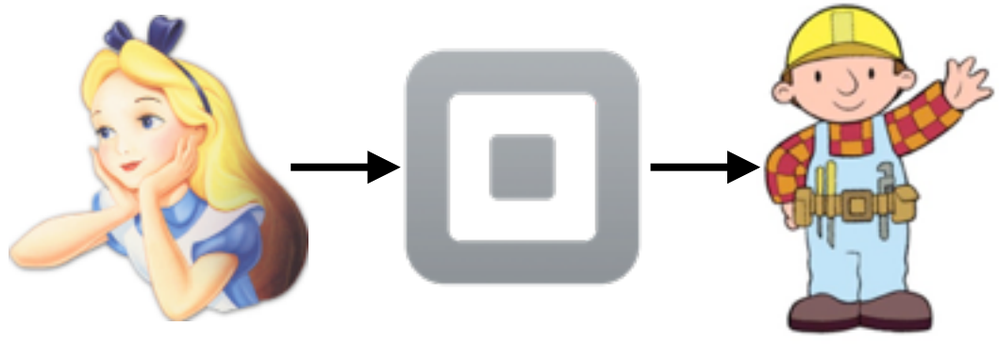

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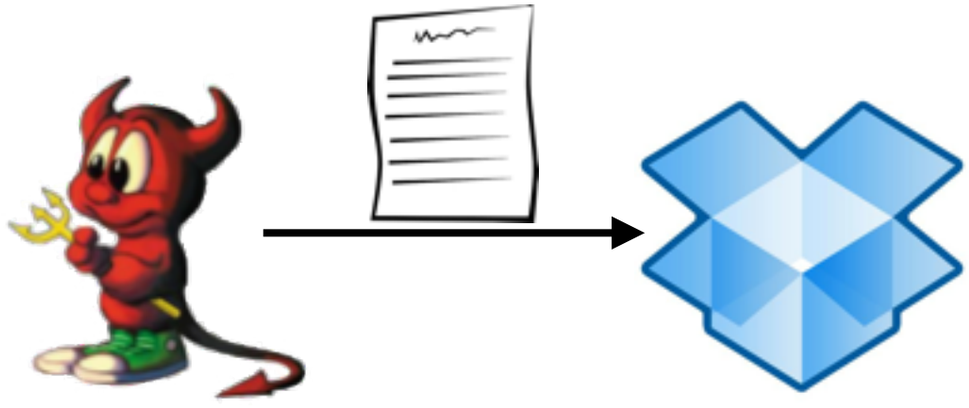

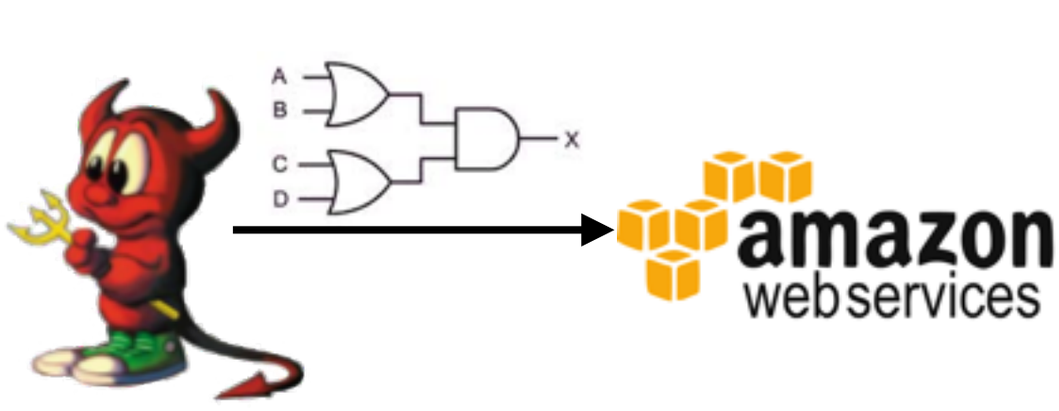

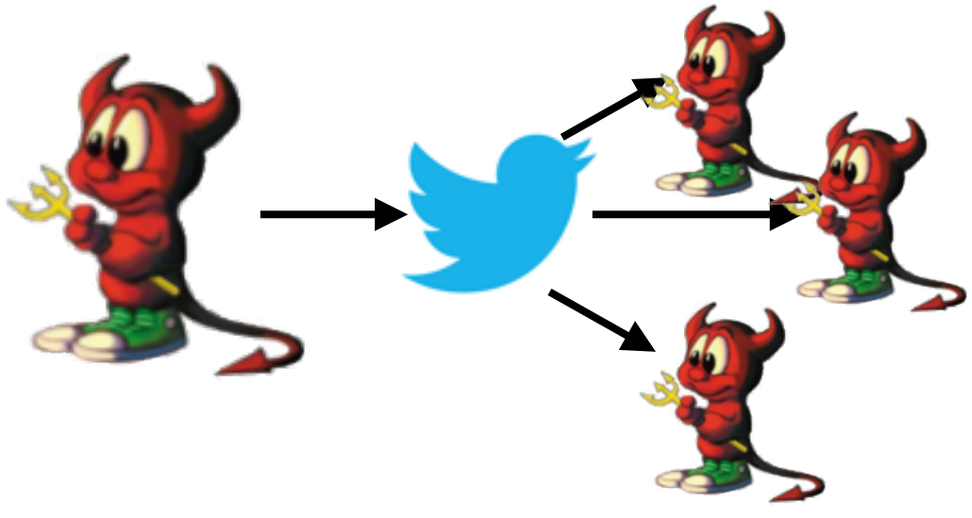

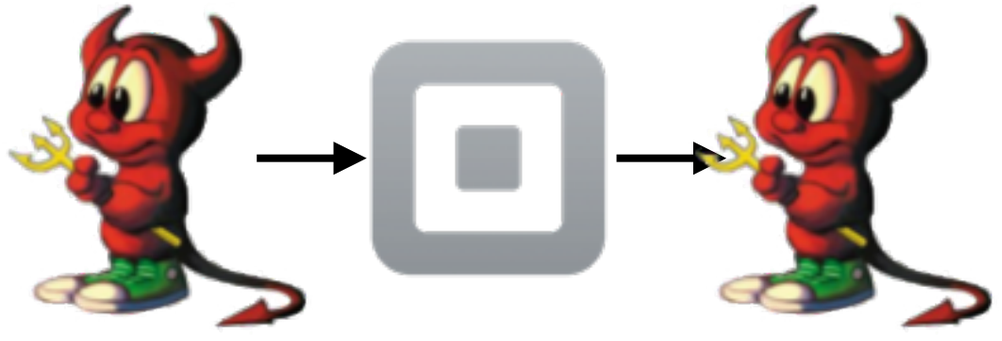

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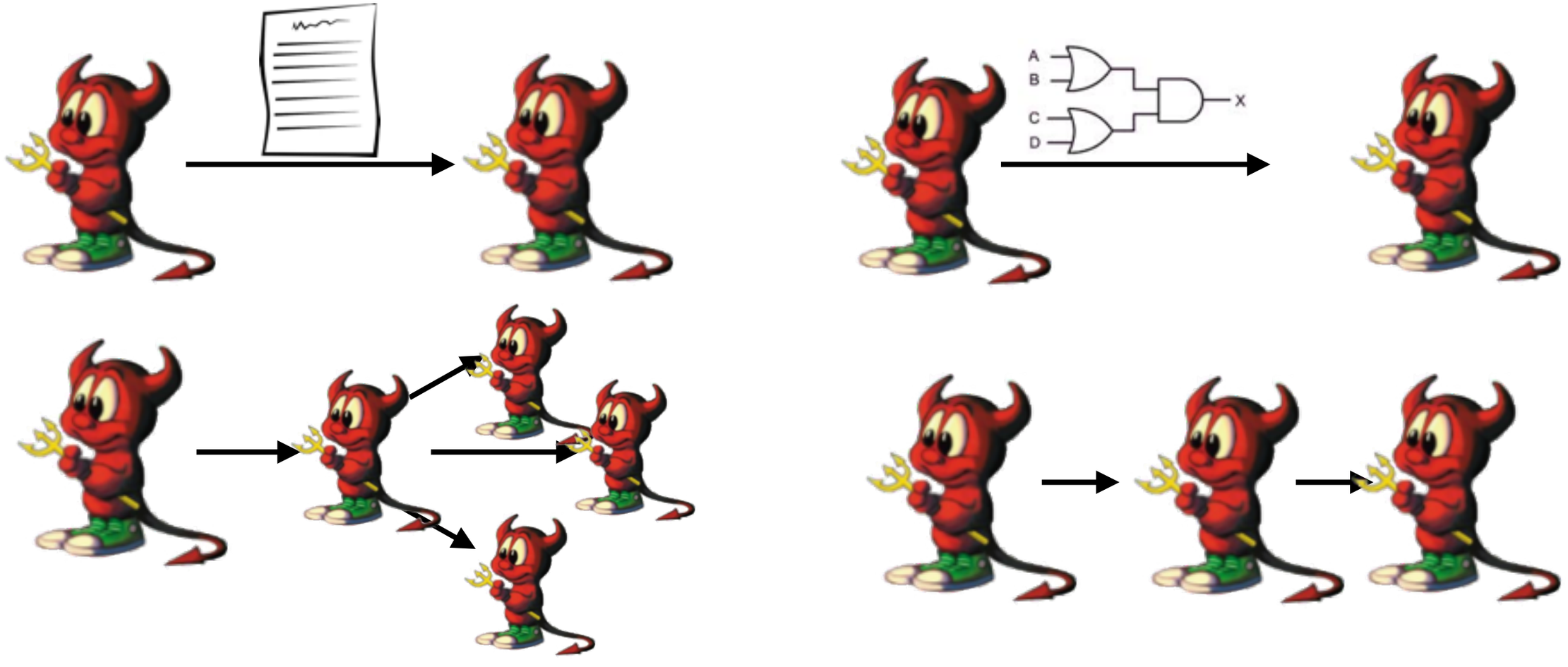

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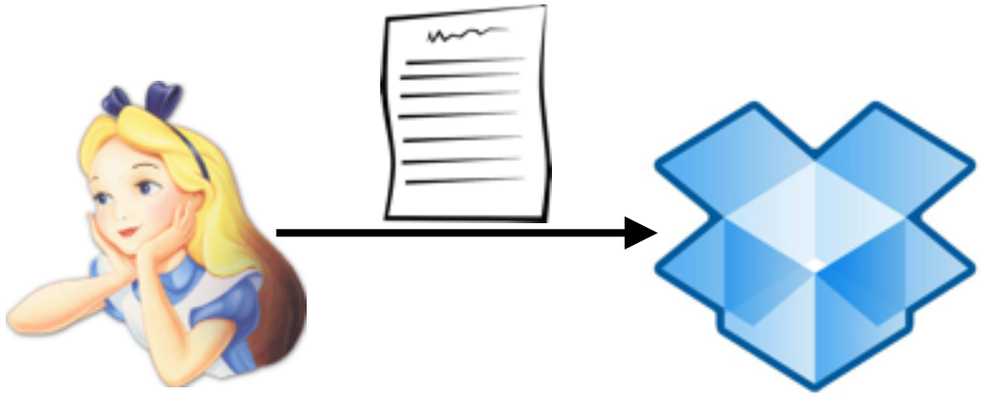

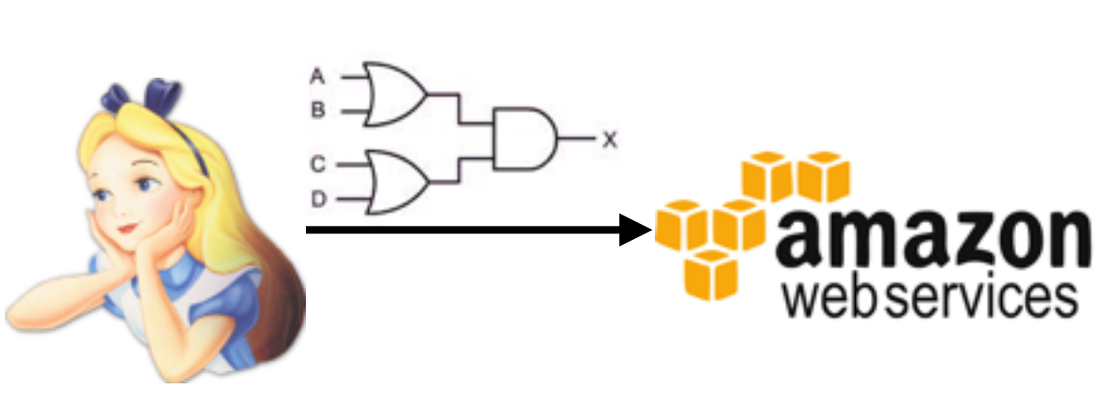

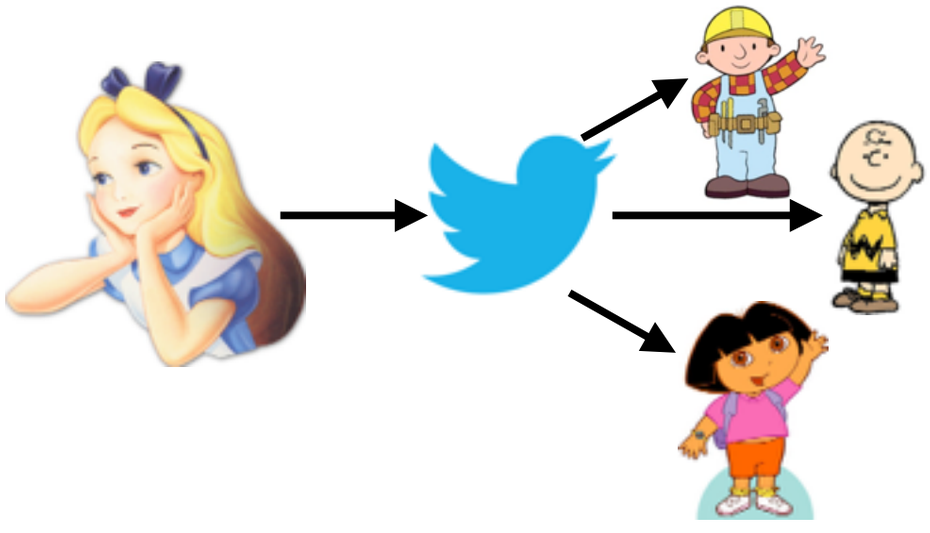

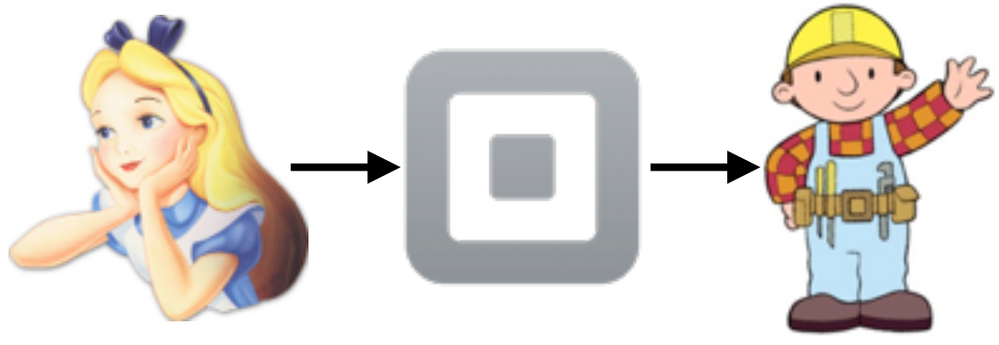

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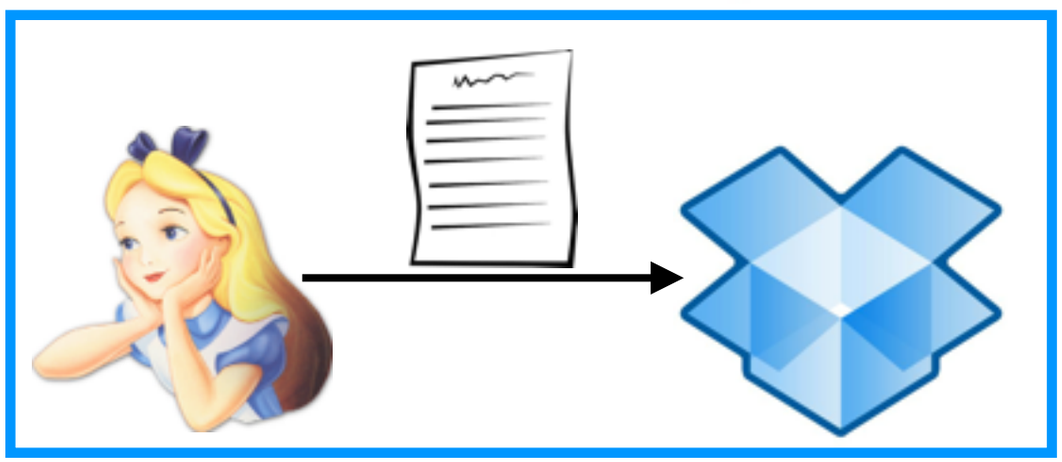

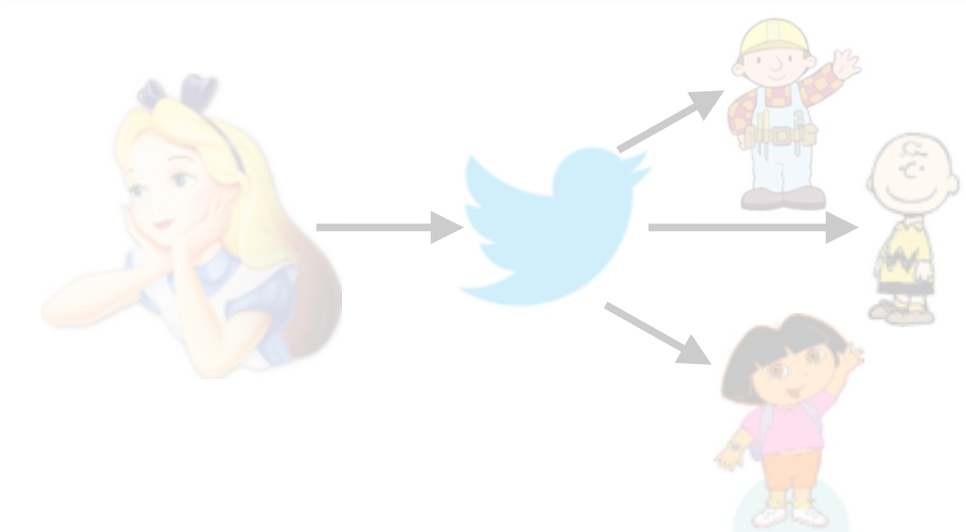

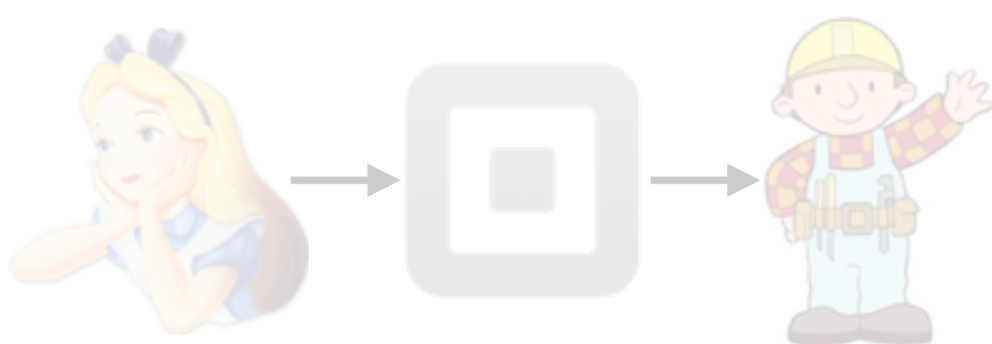

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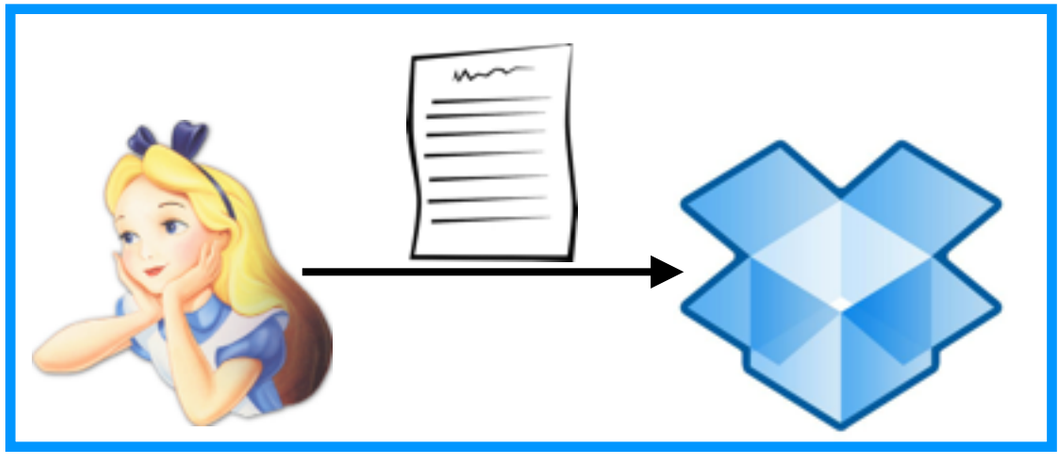

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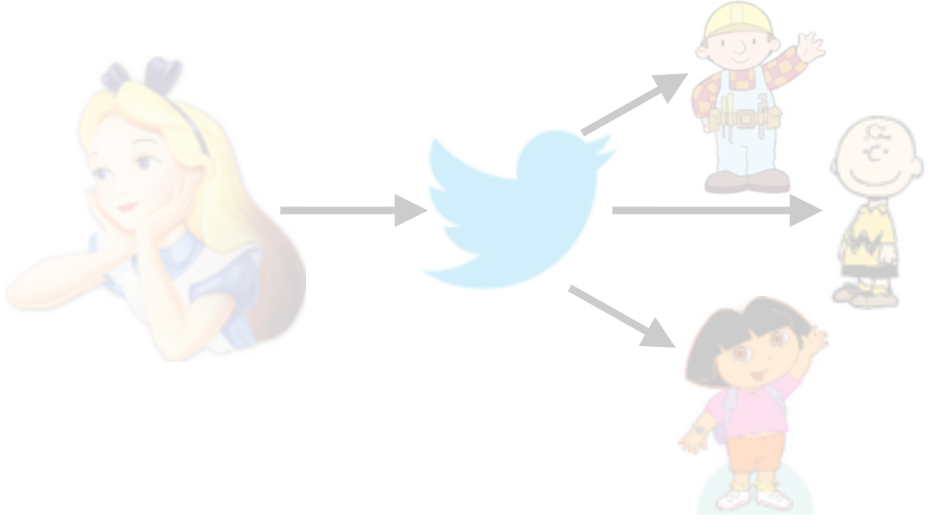

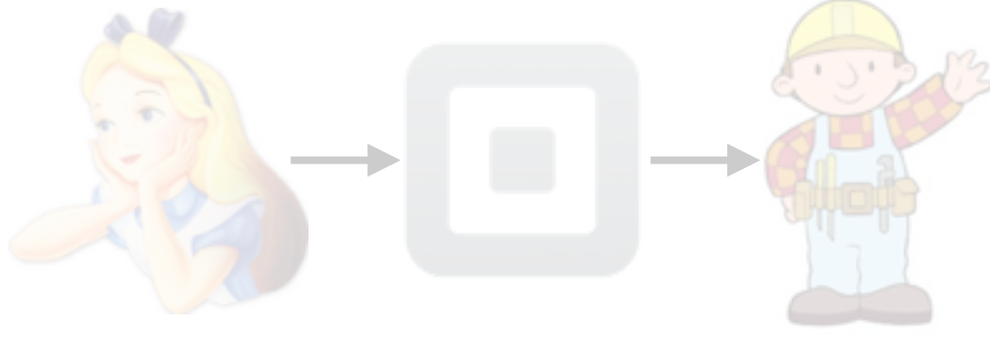

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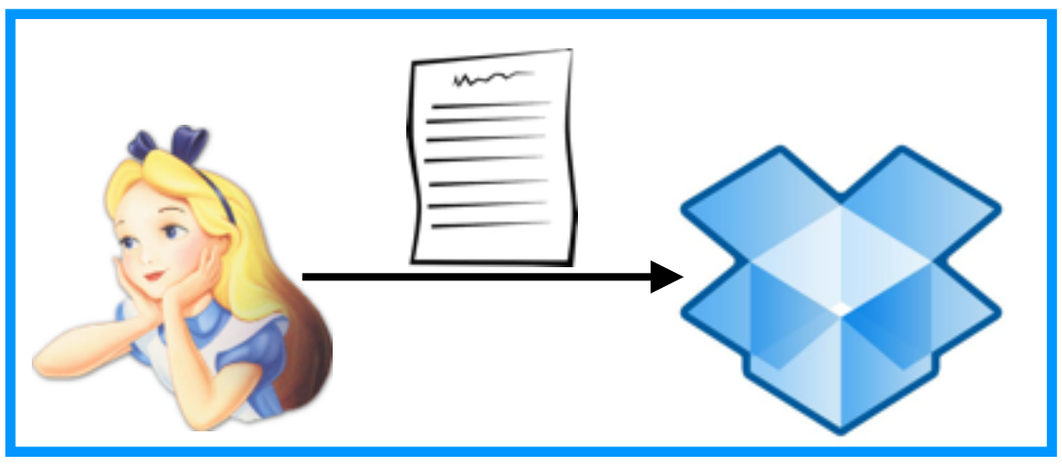
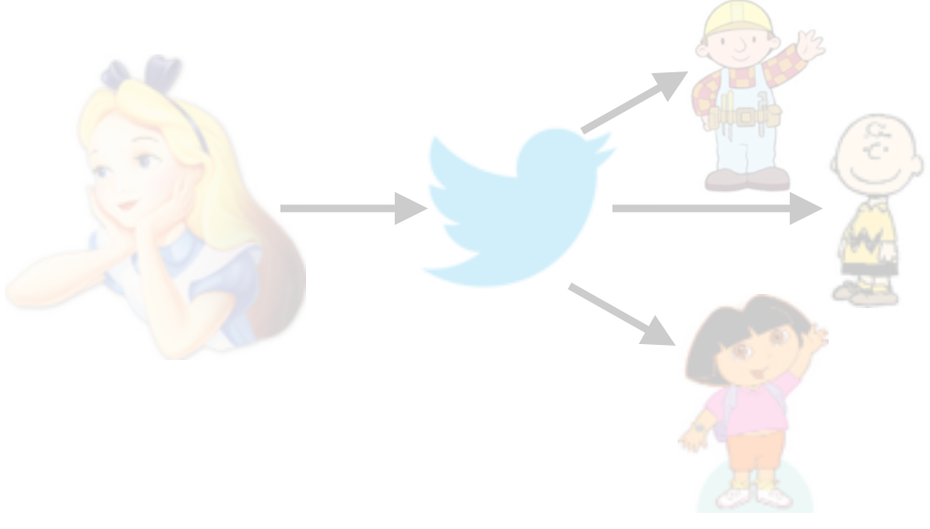
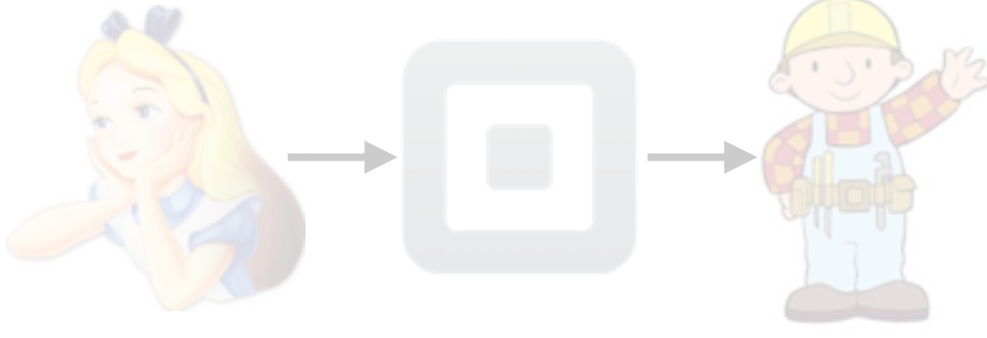


- can Bob retrieve Alice's files?
- can Dropbox read Alice's files?





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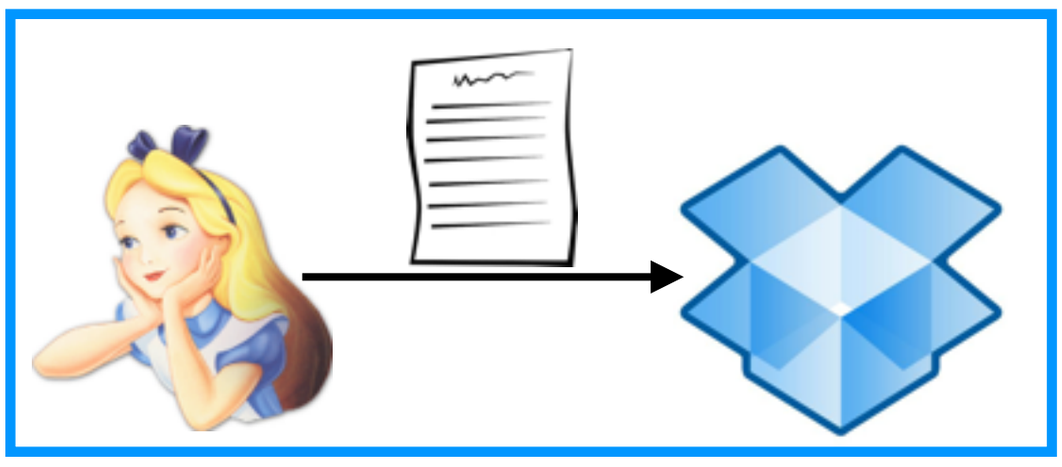

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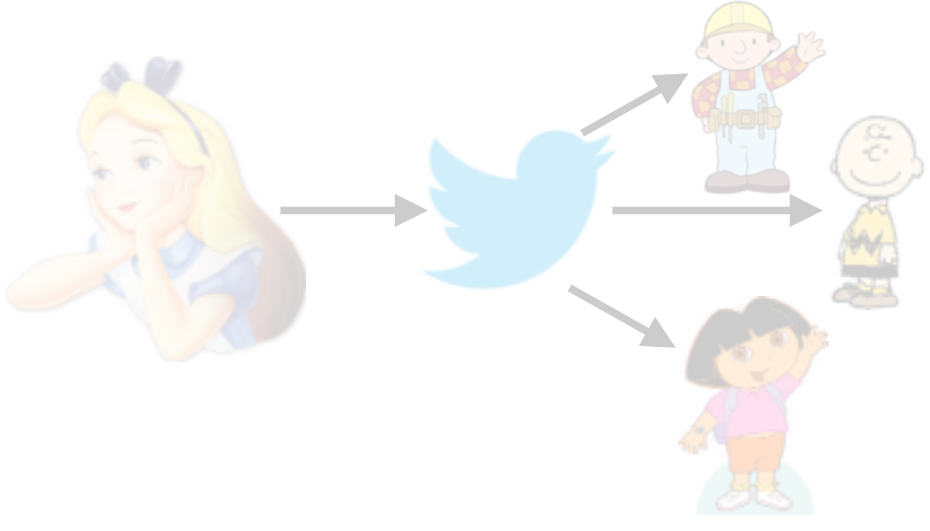

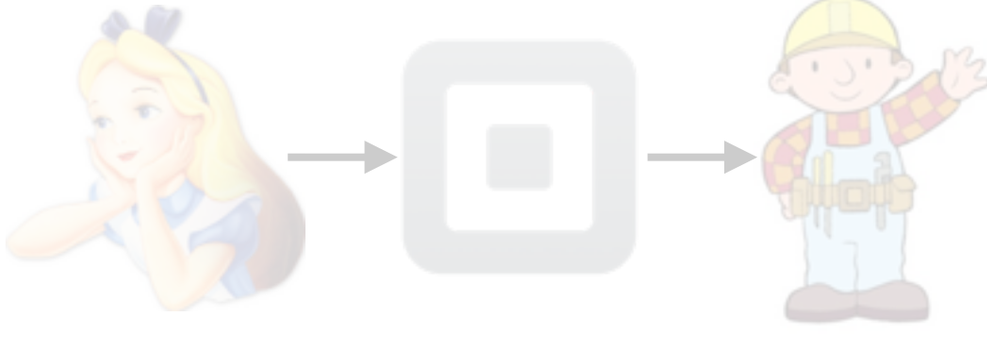

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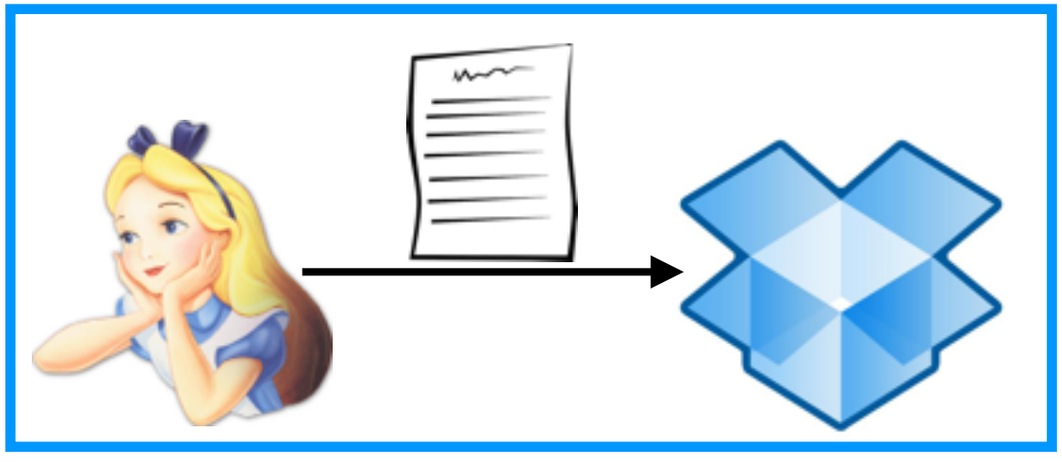

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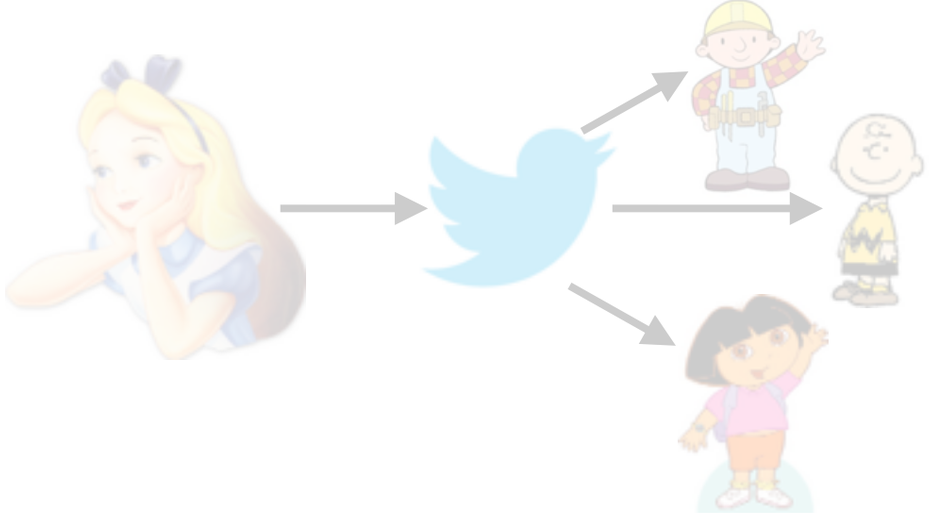

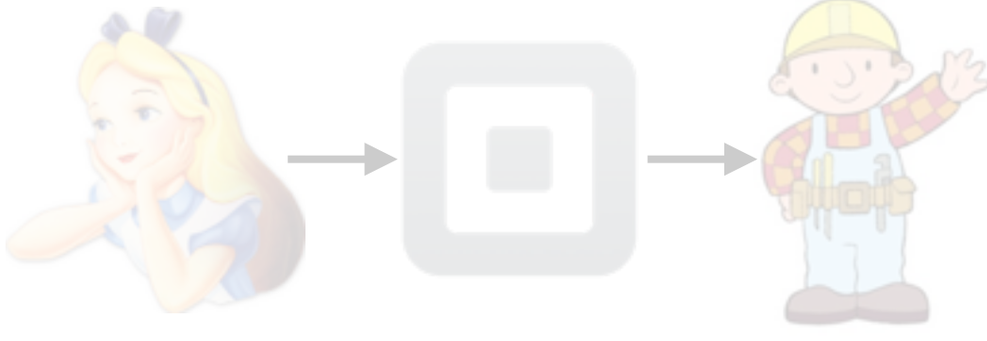

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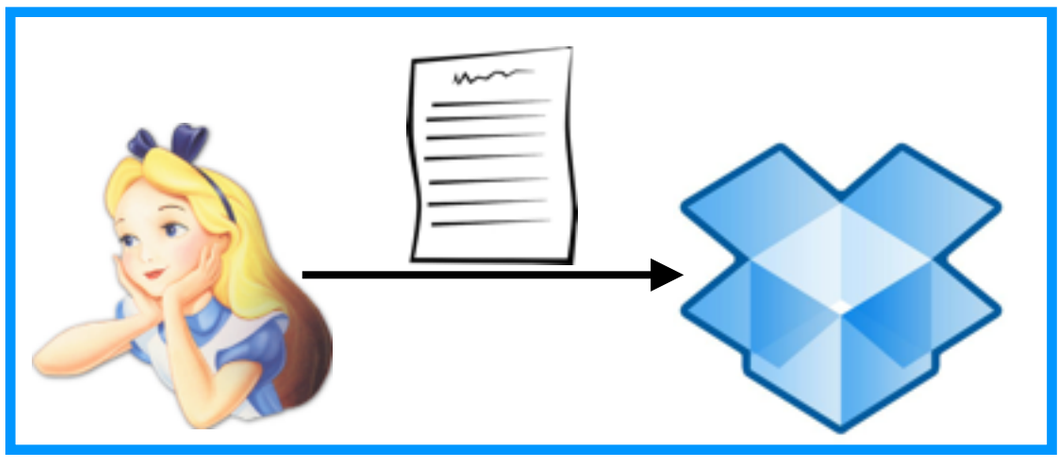

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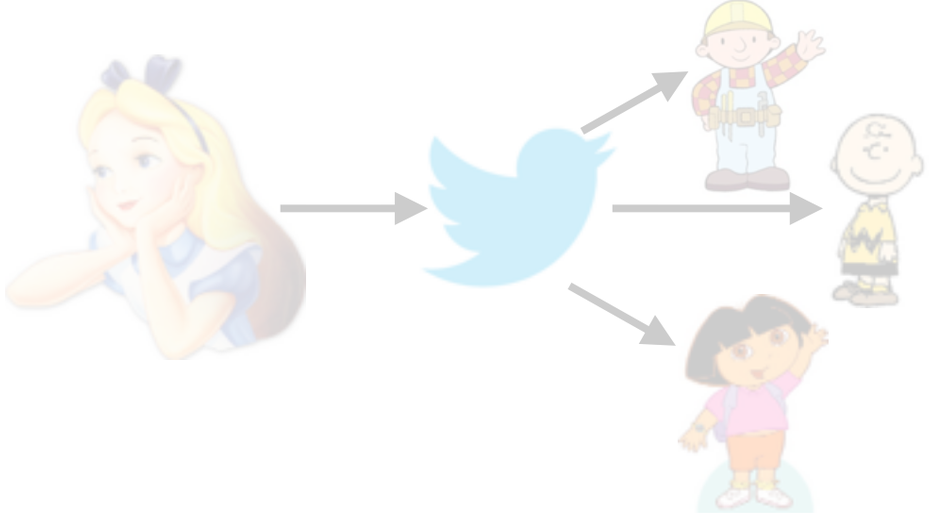
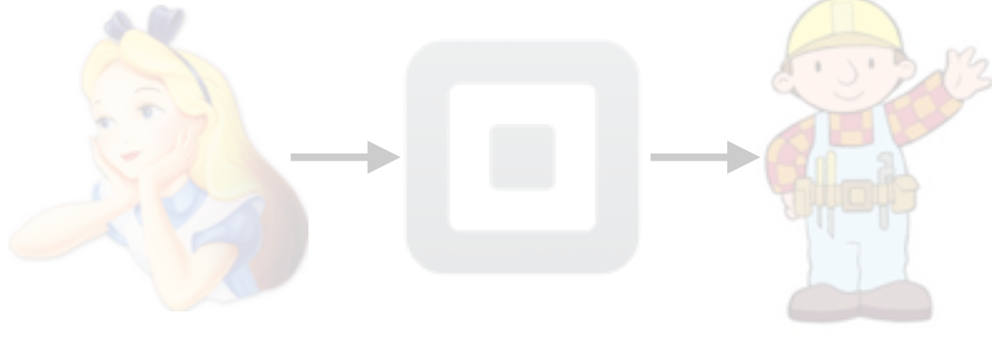
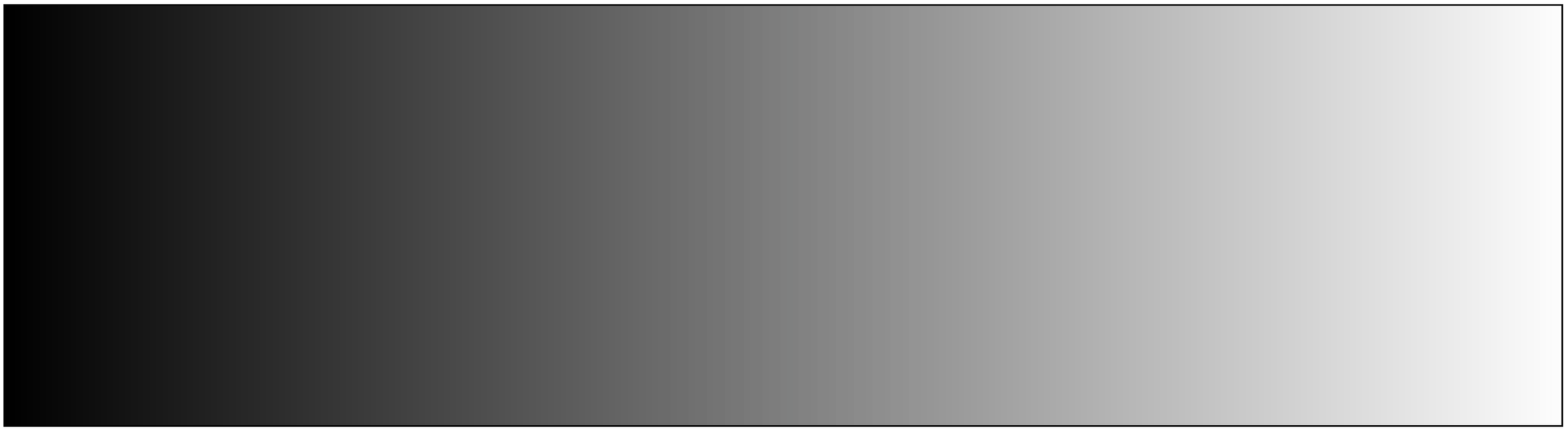




A spectrum of solutions

A spectrum of solutions

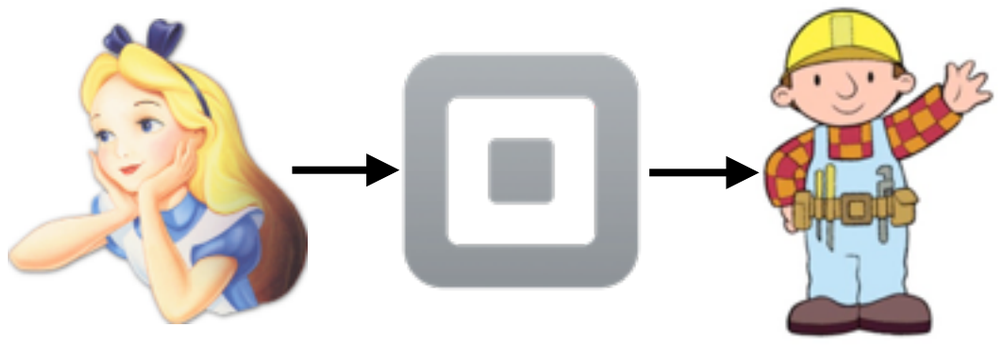


theory practice

A spectrum of solutions

theory

practice

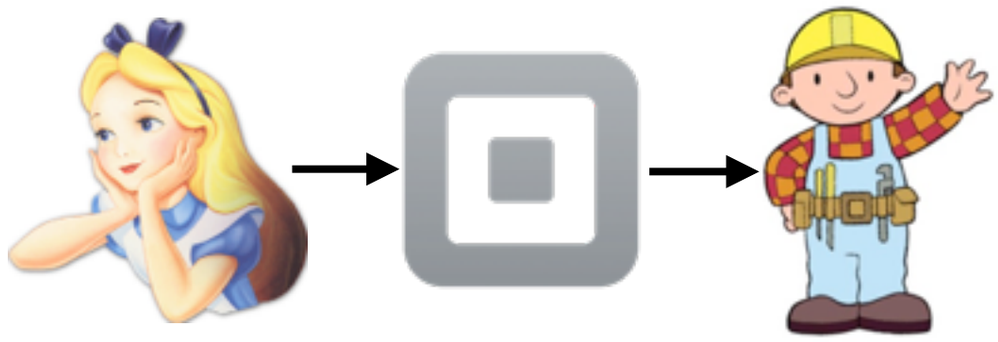


A spectrum of solutions

e-cash [C82]

theory

practice

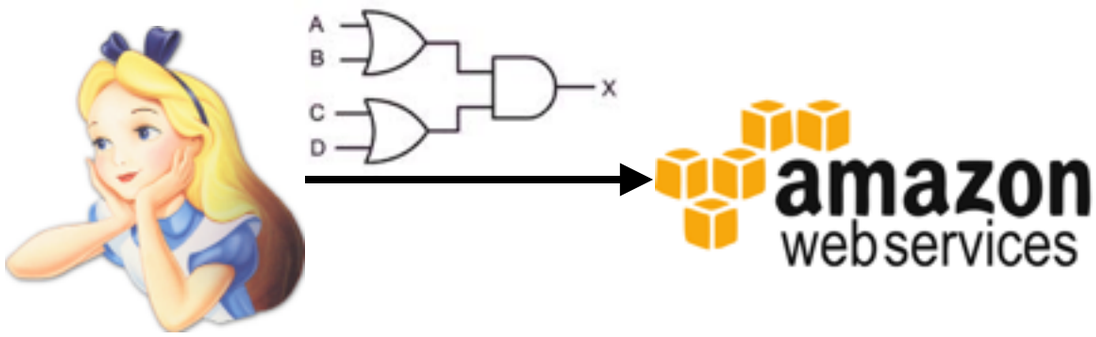


A spectrum of solutions

e-cash [C82]

theory

practice



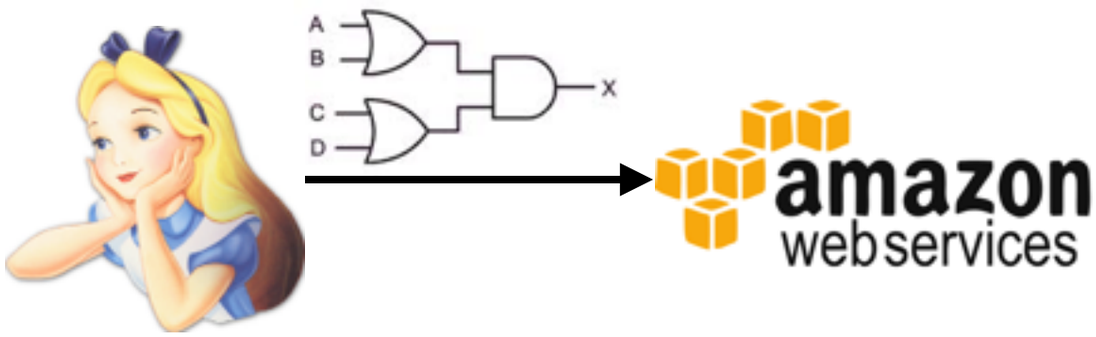
A spectrum of solutions

outsourced comp. [GGP10]

e-cash [C82]

theory

practice



A spectrum of solutions

theory practice

A spectrum of solutions

RKA [B93,K93]

MPC [Y82]

FHE [G09]

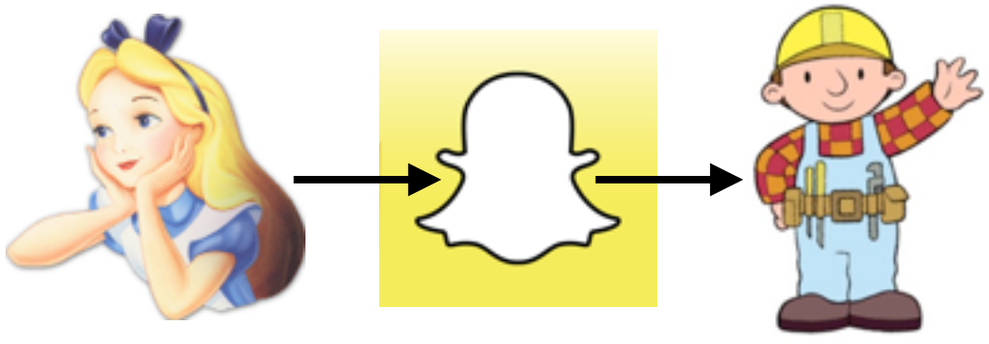
outsourced comp. [GGP10]

ORAM [GO96]

e-cash [C82]

theory

practice



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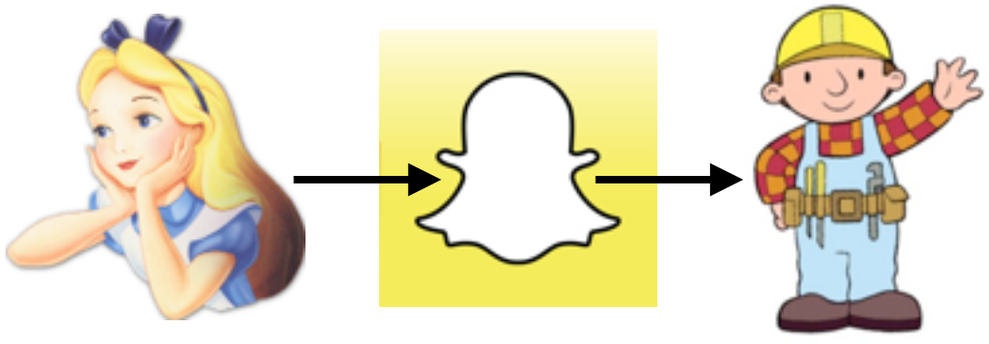
Wickr

theory

practice



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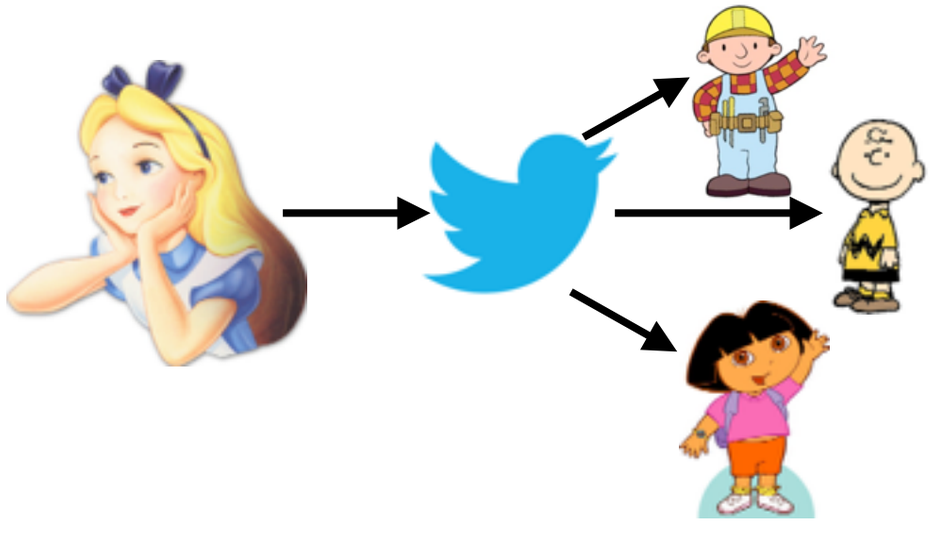
Wickr

theory

practice



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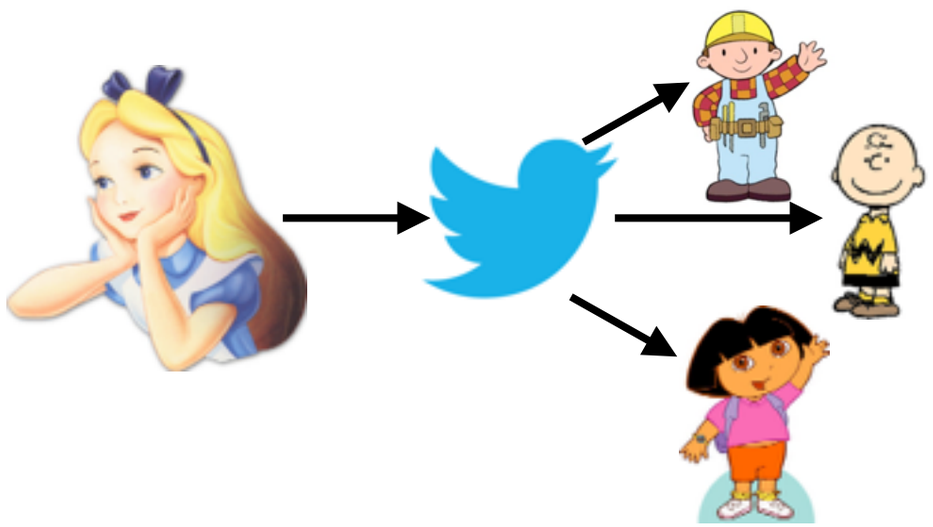
Wickr

diaspora*

theory

practice



A spectrum of solutions

theory practice

A spectrum of solutions

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Bitcoin

SSL/TLS

TrueCrypt

Wickr

Tor

diaspora*

PGP

theory

practice

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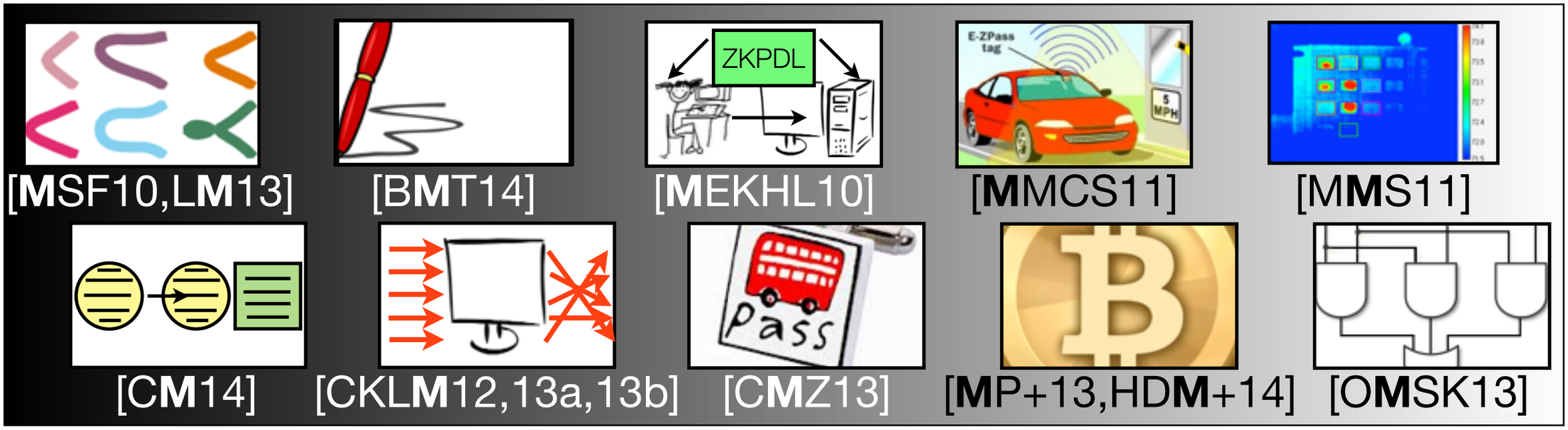
diaspora*

PGP

theory

practice

My research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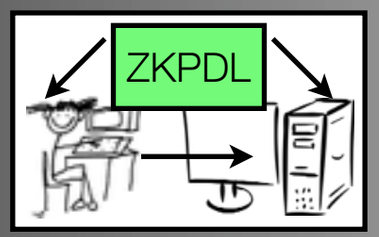
[BMT14]
ZKPDL
[MEKHL10]
E-ZPass tag
5 MPH
[MMCS11]
[MMS11]
[CM14]
[CKLM12,13a,13b]
pass
[CMZ13]
[MP+13,HDM+14]
[OMSK13]

My research

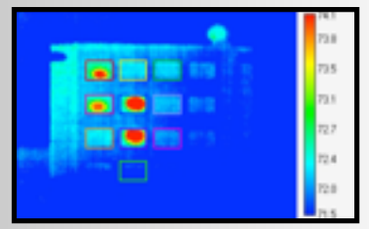

[**M**SF10,L**M**13]

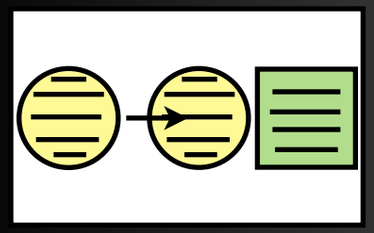

[B**M**T14]

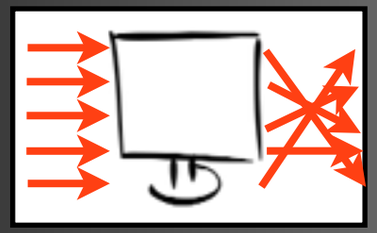


[**M**EKHL10]

[**M**MCS11]

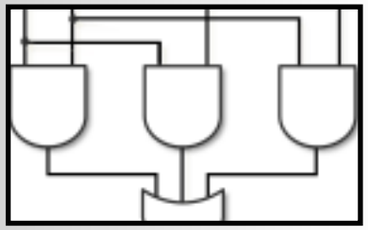

[M**M**S11]


[C**M**14]


[CKL**M**12,13a,13b]

[C**M**Z13]


[**M**P+13,HD**M**+14]


[O**M**SK13]

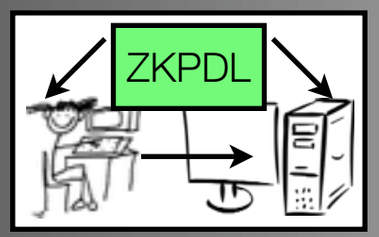

RKA


Bitcoin

My research


[**M**SF10,L**M**13]


[B**M**T14]



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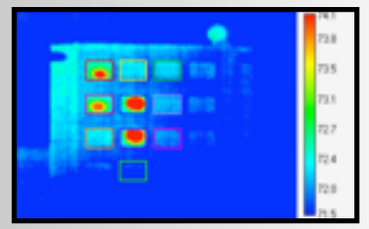
[**M**MCS11]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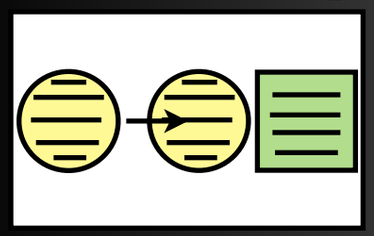
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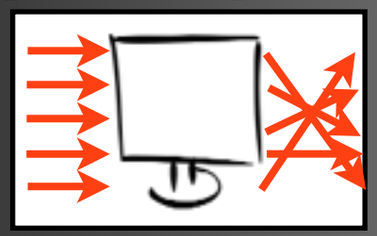
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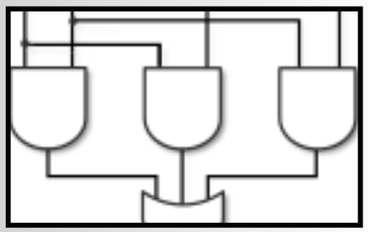
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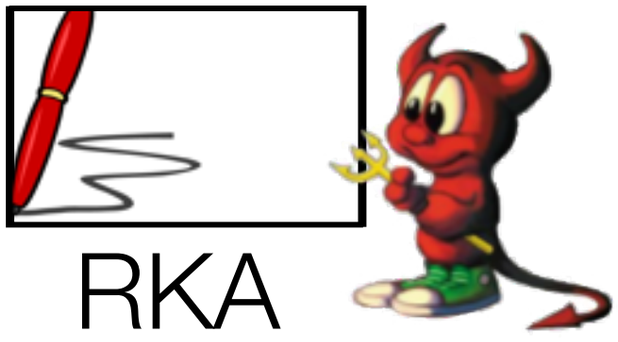
RKA


Bitcoin

My research


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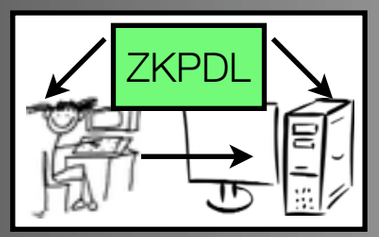

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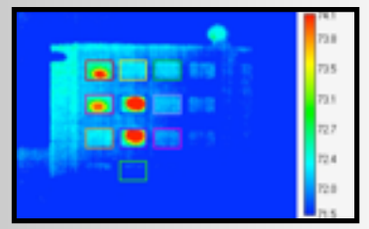
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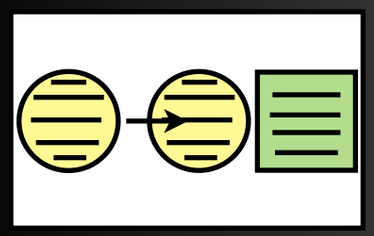
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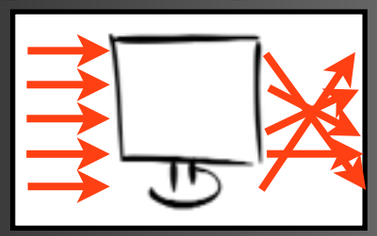
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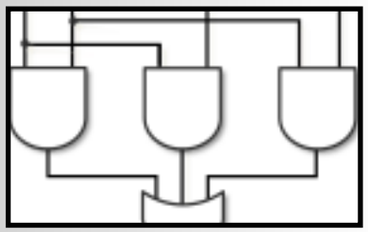
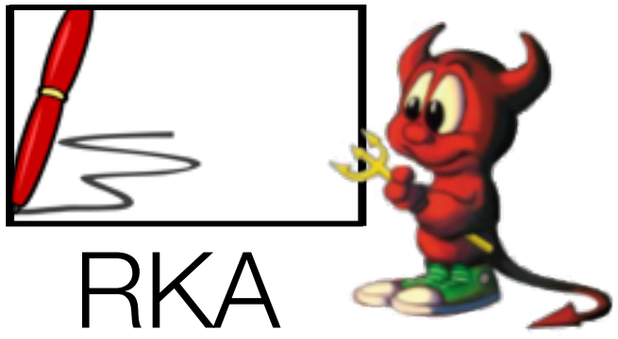

[O**M**SK13]

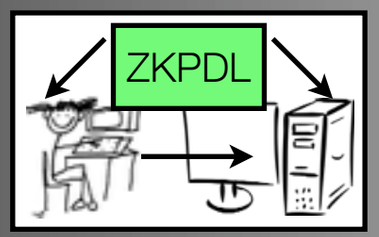

RKA


Bitcoin

My research


[**M**SF10,L**M**13]


[B**M**T14]



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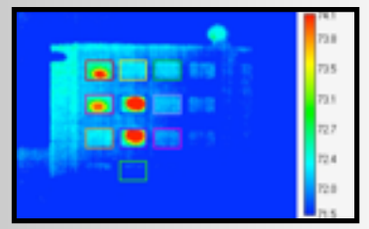
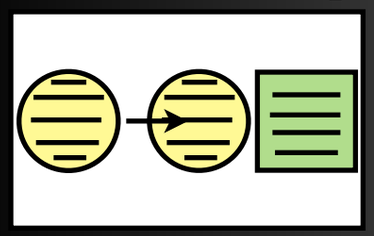
[**M**MCS11]


[M**M**S11]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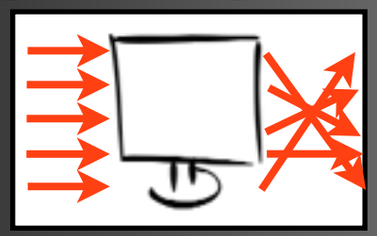
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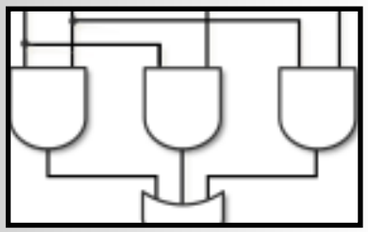
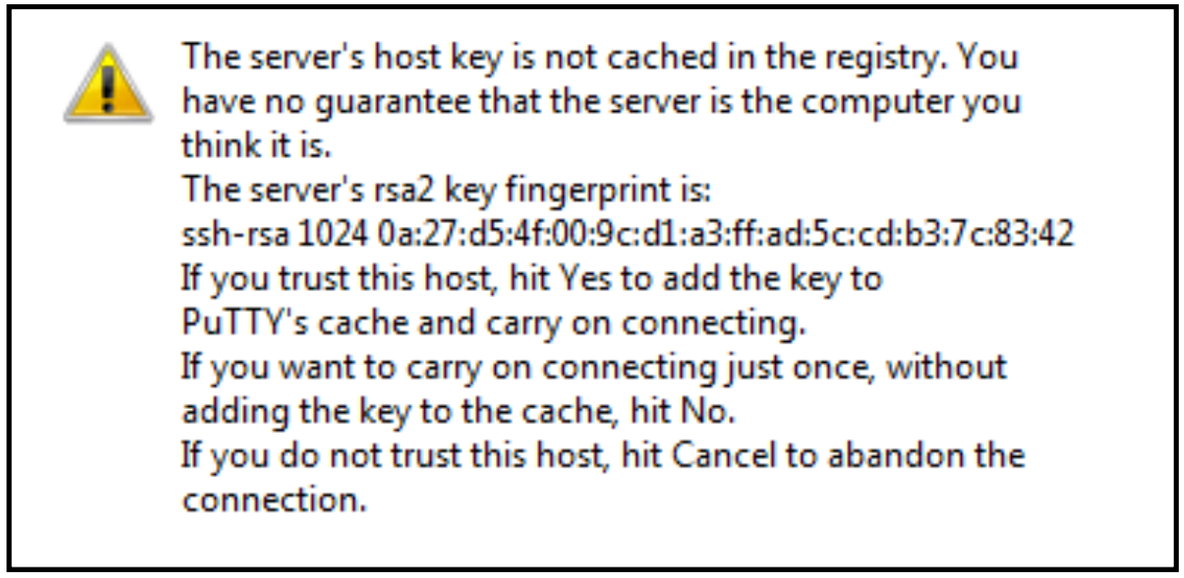

[O**M**SK13]

Digital signatures are everywhere

Digital signatures are everywhere

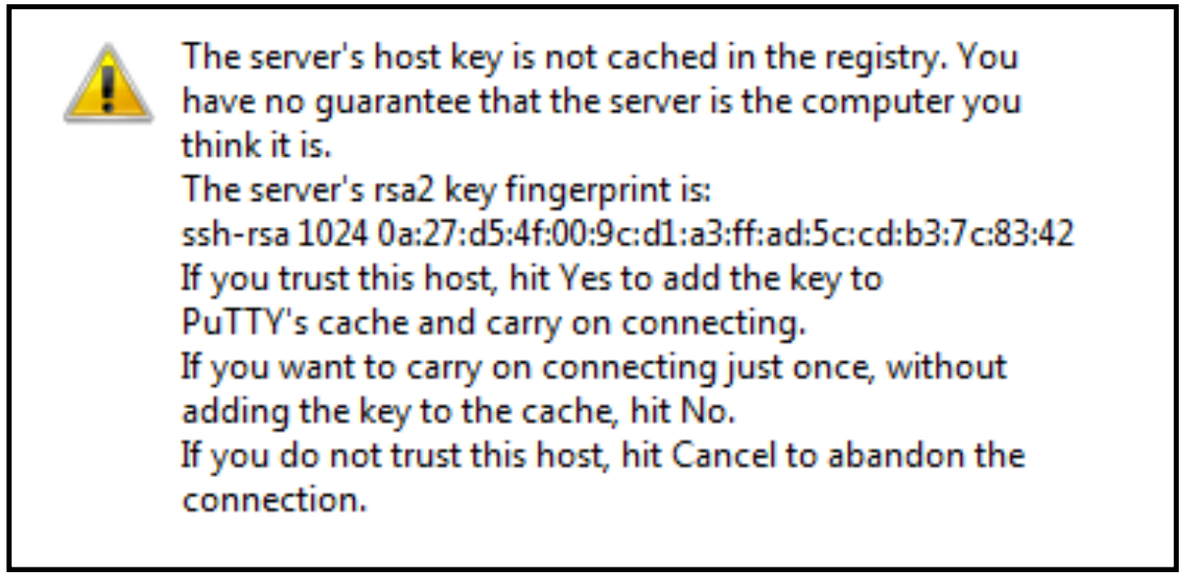


Digital signatures are everywhere

17ijmE4nZstNnevbHLawnhCW9nZ	0.37 BTC
1cTHK2B4D3qg4kj44wxfeQCTE6N	3.11 BTC
1ZhKkzRLLfpNGNHf8qDDH7uRZta	0.20 BTC
1QJ3FK8grGXKEPqVUC1tx6G5Hw	5.16 BTC

The server's host key is not cached in the registry. You have no guarantee that the server is the computer you think it is.
The server's rsa2 key fingerprint is:
ssh-rsa 1024 0a:27:d5:4f:00:9c:d1:a3:ff:ad:5c:cd:b3:7c:83:42
If you trust this host, hit Yes to add the key to PuTTY's cache and carry on connecting.
If you want to carry on connecting just once, without adding the key to the cache, hit No.
If you do not trust this host, hit Cancel to abandon the connection.

Digital signatures are everywhere



Digital signatures are everywhere

Signature Algorithm	SHA-1 with RSA Encryption (1 2 840 113549 1 1 5)
Parameters	none
Not Valid Before	Wednesday, July 20, 2011 5:00:00 PM PT
Not Valid After	Thursday, July 18, 2013 4:59:59 PM PT
Public Key Info	
Algorithm	RSA Encryption (1 2 840 113549 1 1 1)
Parameters	none
Public Key	128 bytes : D5 14 57 A0 96 40 9F 84 08 C6 66 8D EE EC E3 03 B2 66 85 AC 5D BB 1C EF 15 93 FD 1F 20 A7 10 49 24 5B 39 D2 60 C8 9A DC C0 CE 40 34 E6 59 95 B6 52 50 FE 08 25 45 57 73 5F 3A ED 5F DF B6 5C 9D 8A 9C 62 FD 0F 61 BE DC F6 87 1D 80 9D 7F 7C 17 13 77 64 3C 47 F3 87 24 1F 60 61 E0 81 11 46 E4 DC 50 5C 39 53 E6 68 3D 86 3C 55 87 C8 BE FC 87 13 D9 5A AA 5D CC 3F 07 C1 74 CD C2 5E 27 16 11
Exponent	65537
Key Size	1024 bits
Key Usage	Encrypt, Verify, Derive
Signature	128 bytes : 84 FB EF B0 38 C7 B4 E6 BB 74 41 34 6C 52 6F 0E F7 7B 67 D4 D7 AD A7 EF 03 36 EF C0 40 DE 80 D3 0A A6 3C C9 C3 9E 31 52 07 EA 0F 44 63 EA 51 C2 D0 CE 9B A1 6D 99 F8 29 39 2C 40 98 67 12 8C A7 BF 43 30 D2 02 63 B3 F8 0C 36 85 50 8F 29 C2 87 CD E6 F0 EA 57 F2 A4 81 0E 94 B0 D8 46 67 2C 20 AE B6 89 64 A6 B0 DA 8E CF D4 09 7F 57 DC 9C 32 05 06 62 B2 08 14 FE 8B EA 11 13 BC F7 3B 7E F5

OK

```
-----BEGIN PGP SIGNATURE-----
Version: GnuPG v1.4.11 (GNU/Linux)
Comment: Using GnuPG with Thunderbird - http://www.enigmail.net/

iQEcBAEBAgAGBQJSbpK5AAoJEKAl9HCTr8nwh8sIAIlViE5OmpHbzpcatKMdUL9q
0ehAanFyH9WEVxHuv/DAW9Mq35hsYRJL+2wDBUbyeCtCIhjgfW0jmgsYc0MevQva
w0MUOleYwBOVkDM6l6E5KN+fRC5qqjeLZvFO2yVrEdltCZeRvNzKm1MREbKnSBPd
vkMAW/G/U2dA9GmQjm3lw6Av8Sakh8FC+nGGOwtKHl3TpWK41RdqR503M7tBD1Ov
+d9zRchtD5Rs2X43CSTXq5g02zIBcCqarfLKGvPLHOc+4YW+9+9H9V/LT7vTDIDe
WWvIrYWM21p8eShdcoukW3aar3ovNqQ6B/8xzLeblAcruvIl3ejE2xAR20Btm50=
=jT/5
-----END PGP SIGNATURE-----
```

17ijmE4nZstNnevbHLawnhCW9nZ	0.37 BTC
1cTHK2B4D3qg4kj44wxfeQCTE6N	3.11 BTC
1ZhKkzRLLfpNGNHf8qDDH7uRZta	0.20 BTC
1QJ3FK8grGXKEPqVUC1tx6G5Hw	5.16 BTC

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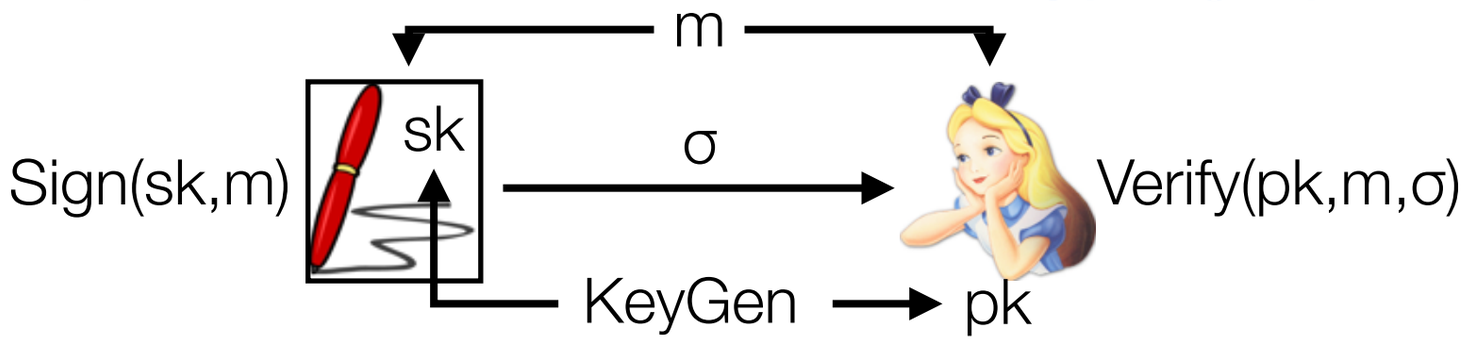
Practical security of digital signatures

Practical security of digital signatures

Signatures are proved secure in standard cryptographic models



Practical security of digital signatures

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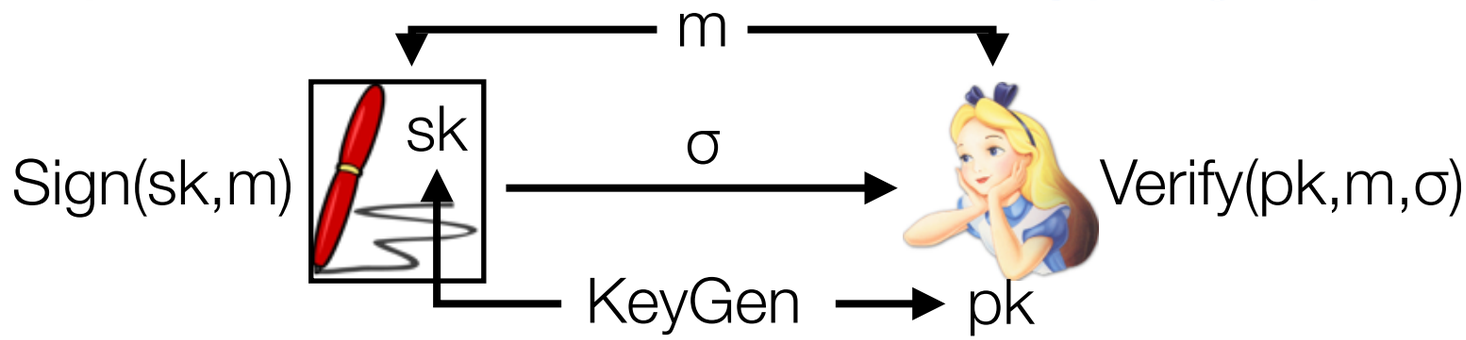

Standard model is useless against side channels and fault injection

Practical security of digital signatures

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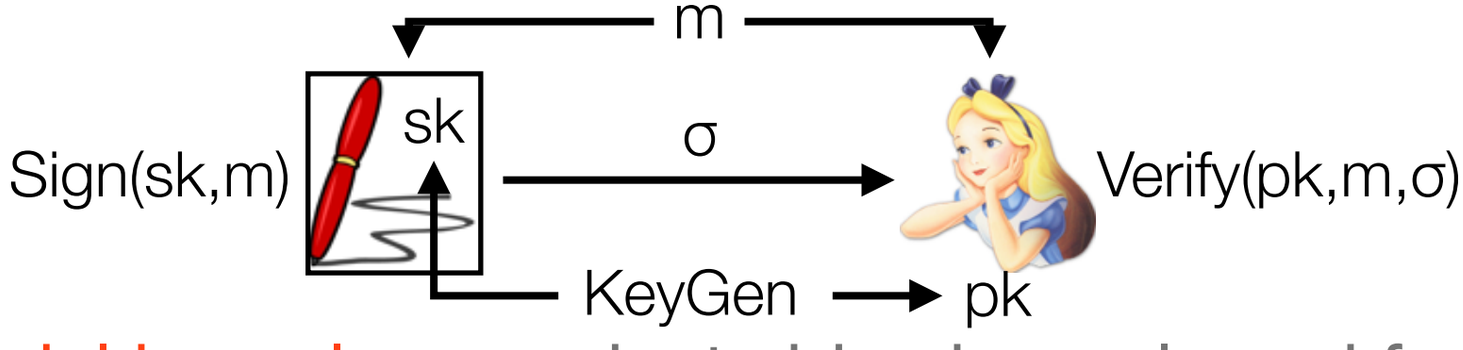
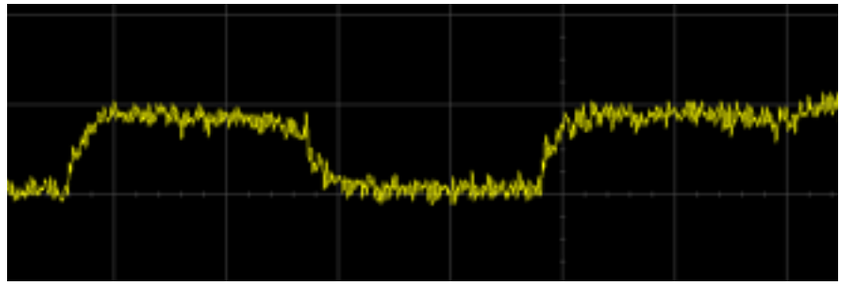


Standard model is useless against side channels and fault injection



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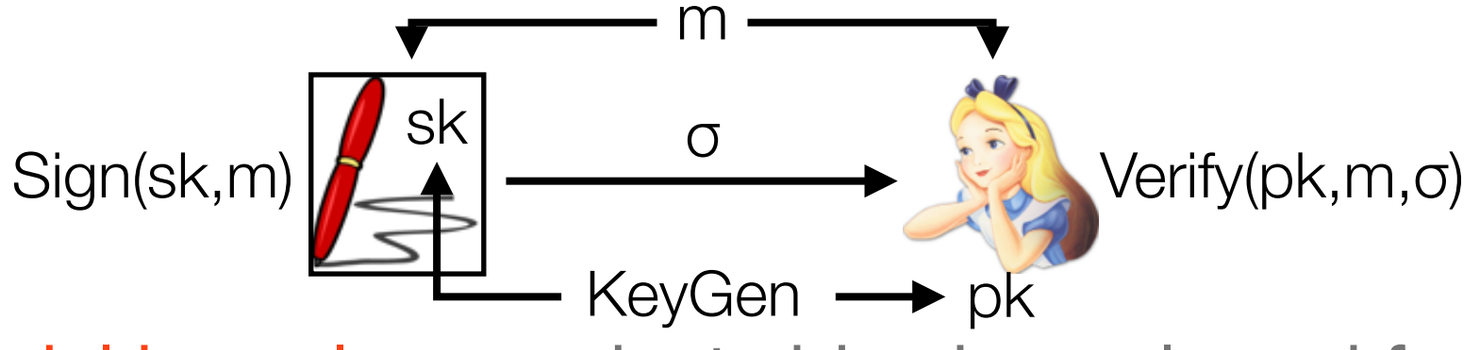
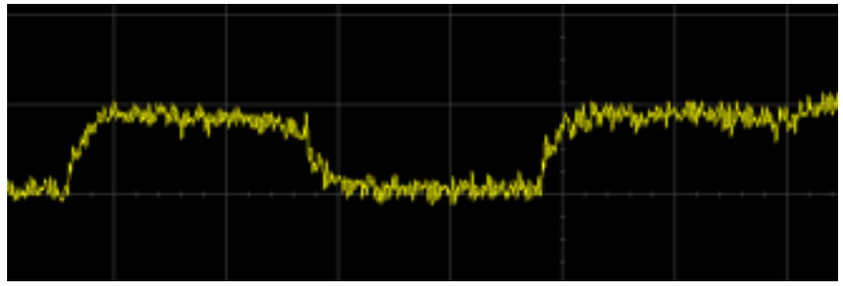
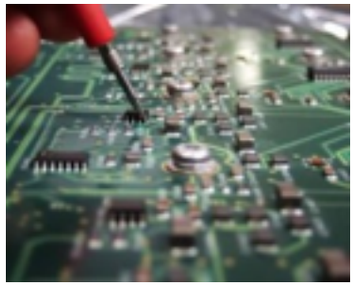


Standard model is useless against side channels and fault injection





Practical security of digital signatures

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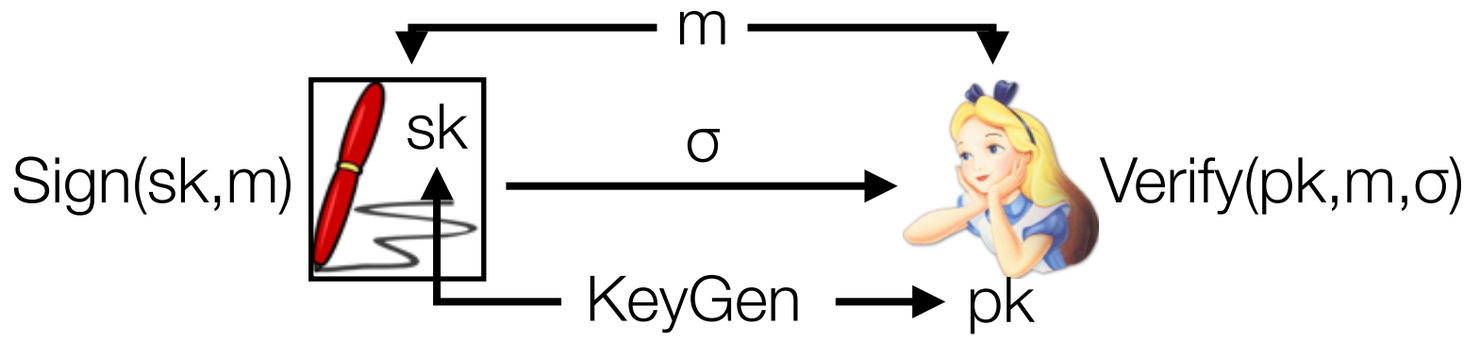

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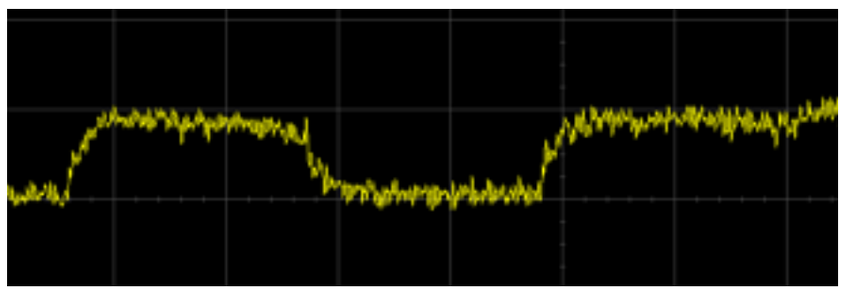

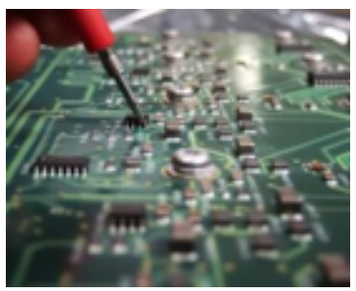

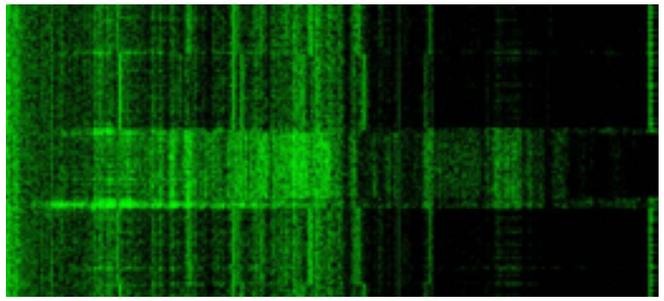

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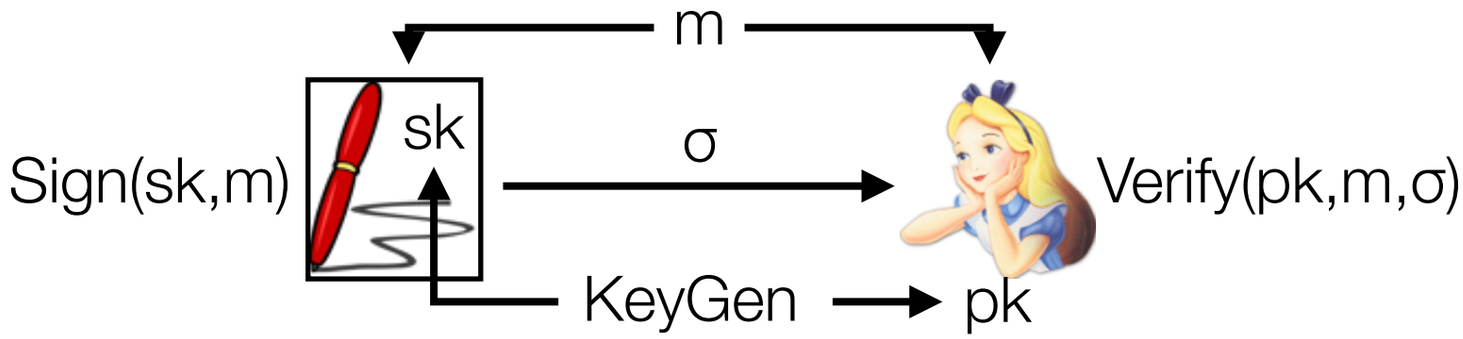

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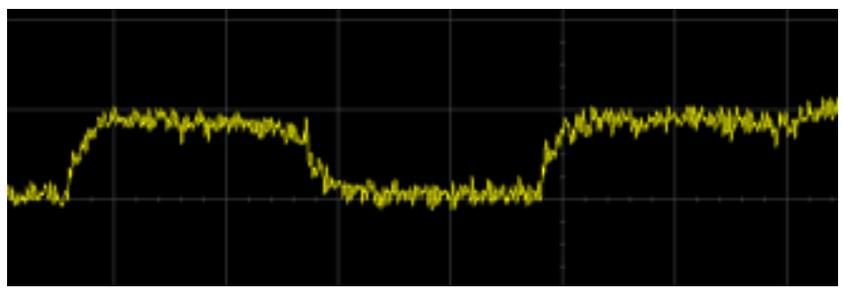
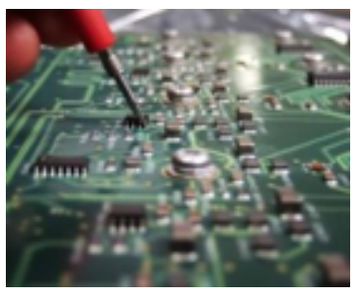
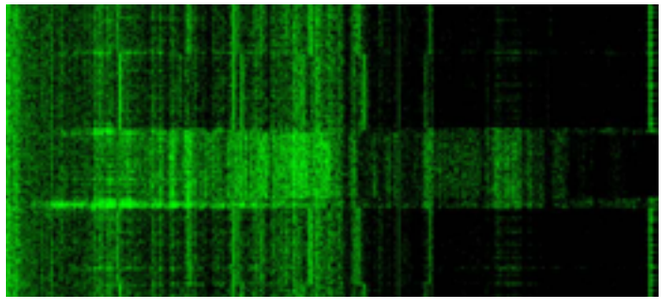

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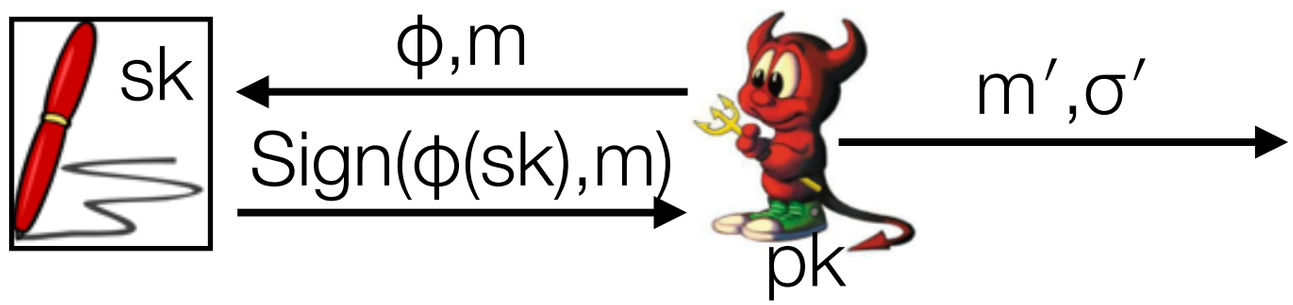

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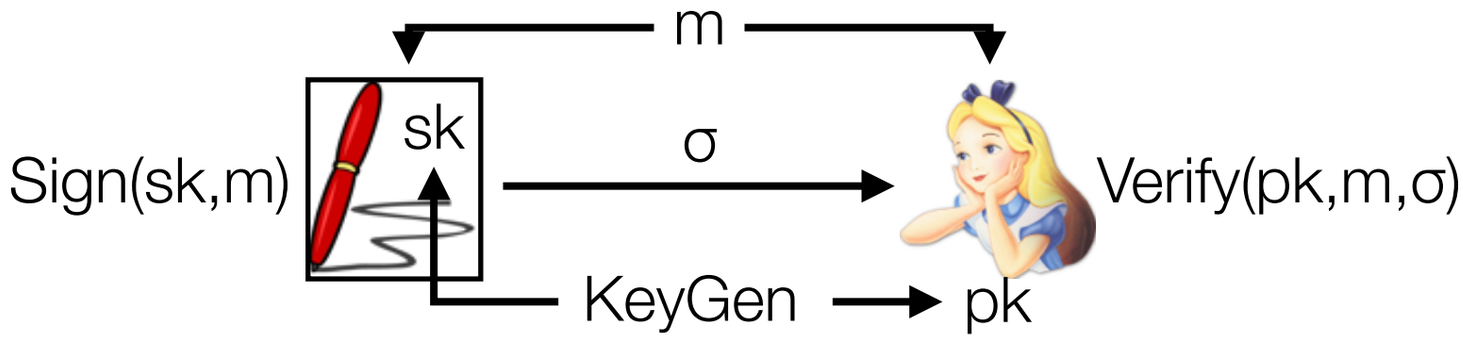

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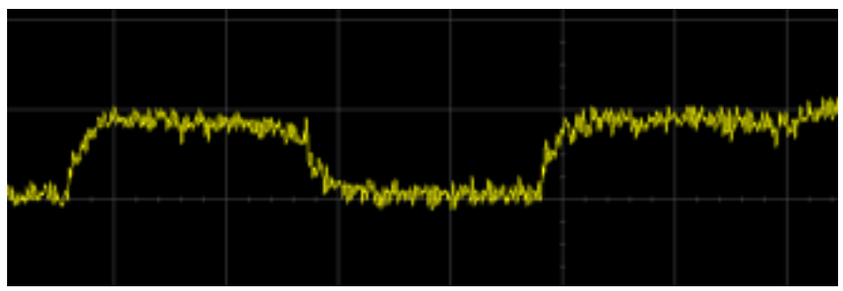
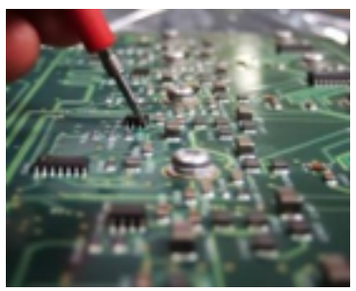
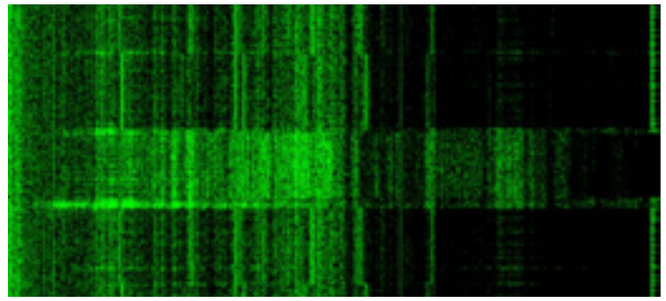

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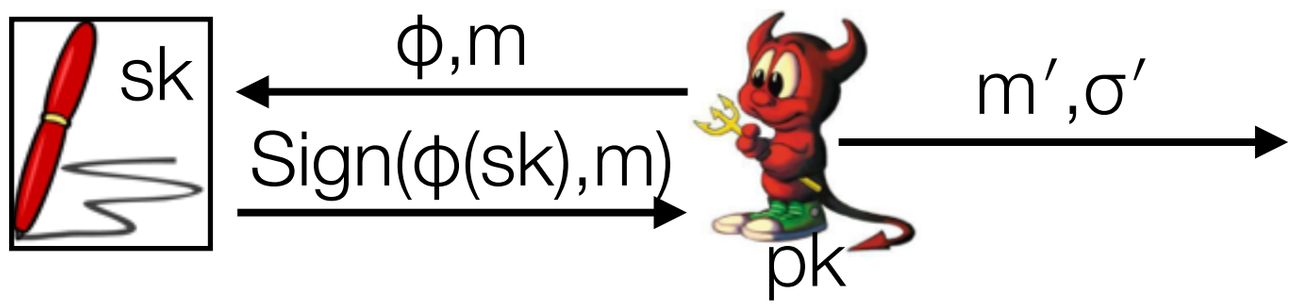

Our research can help create better RKA schemes

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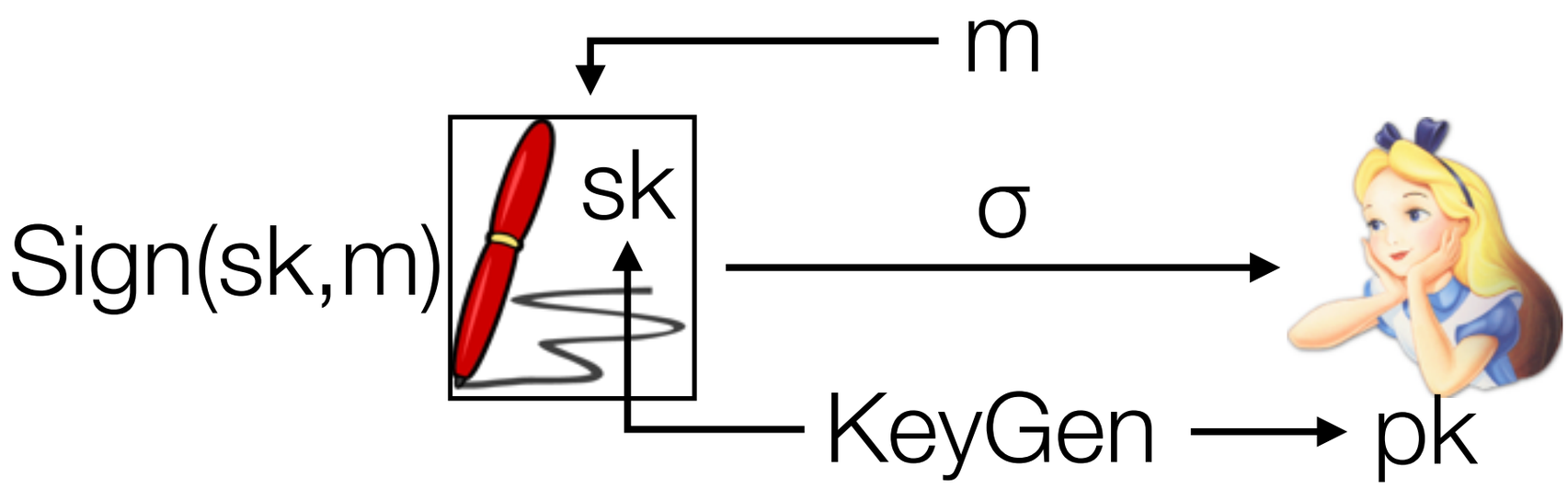

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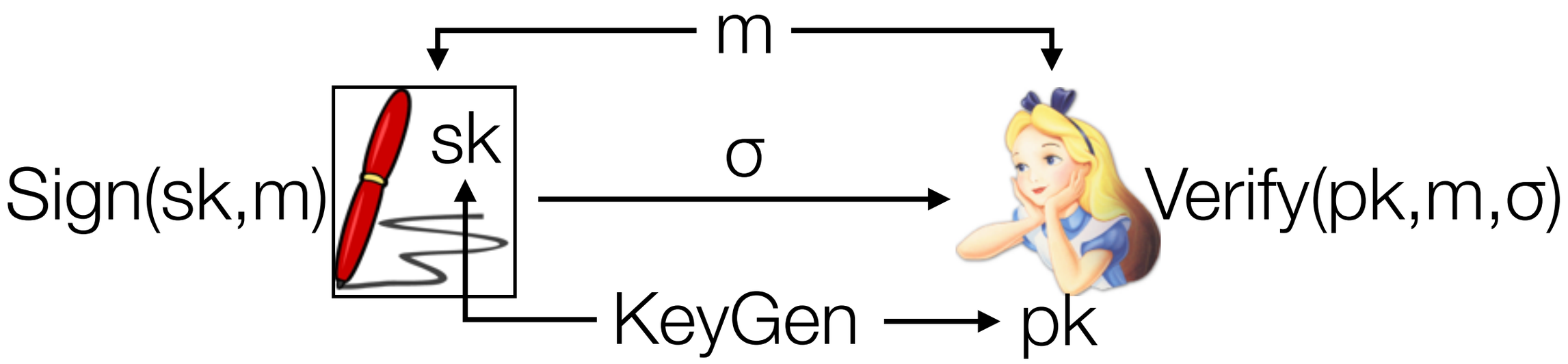

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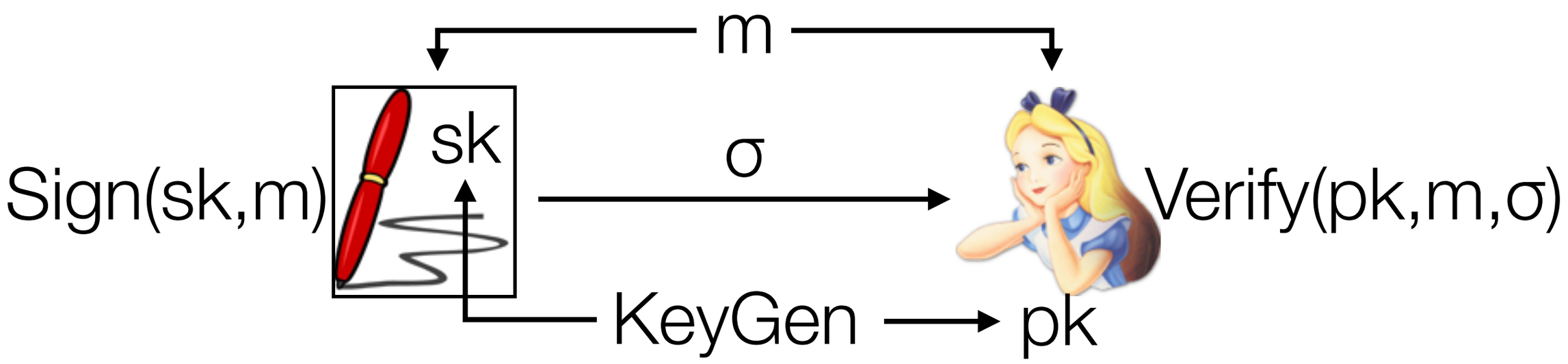

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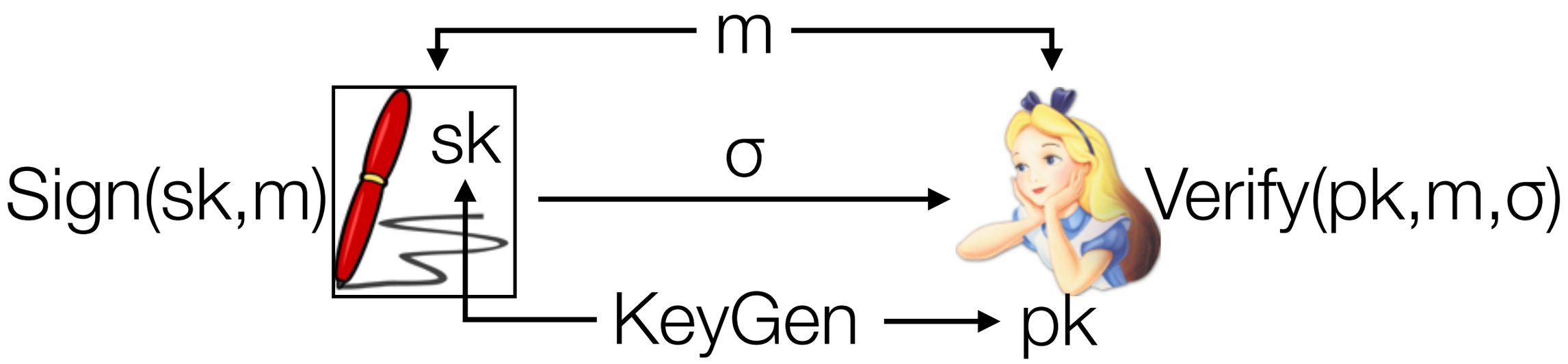

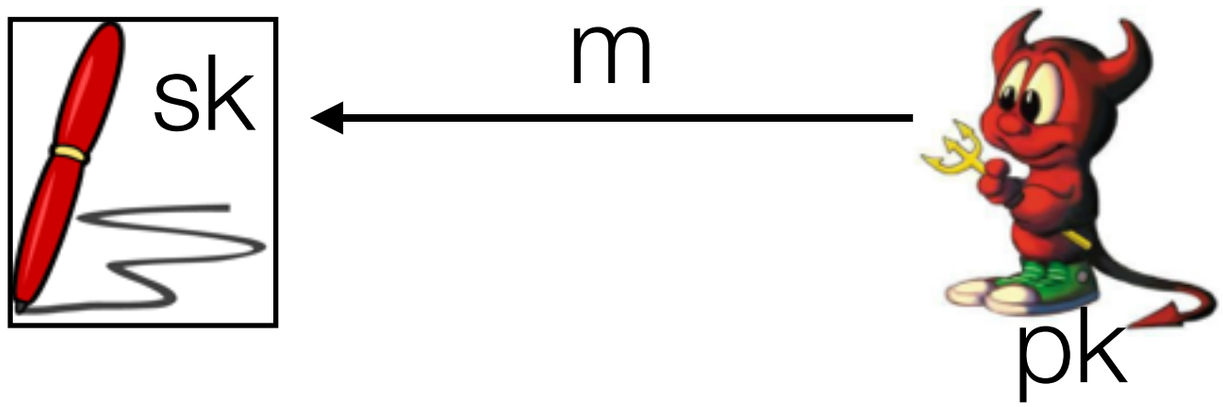

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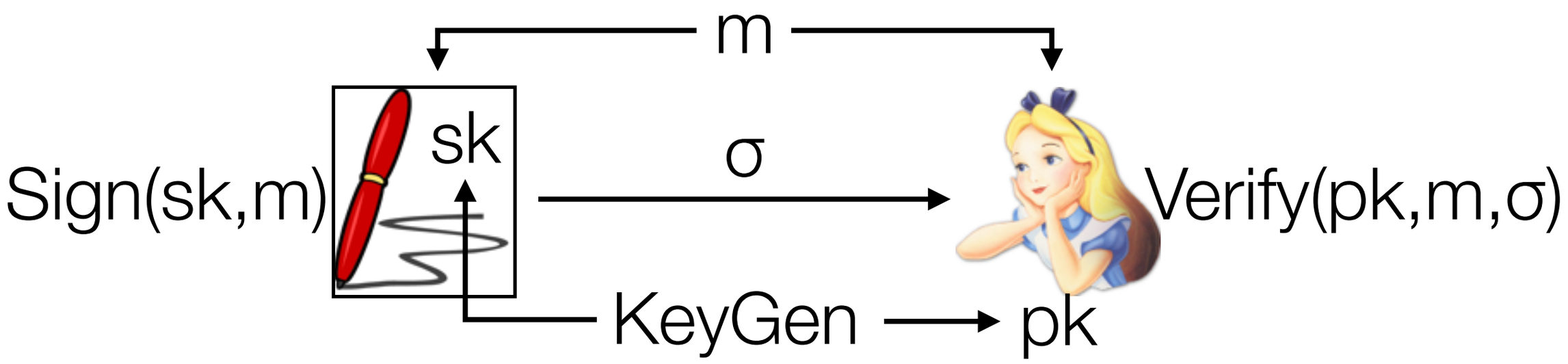

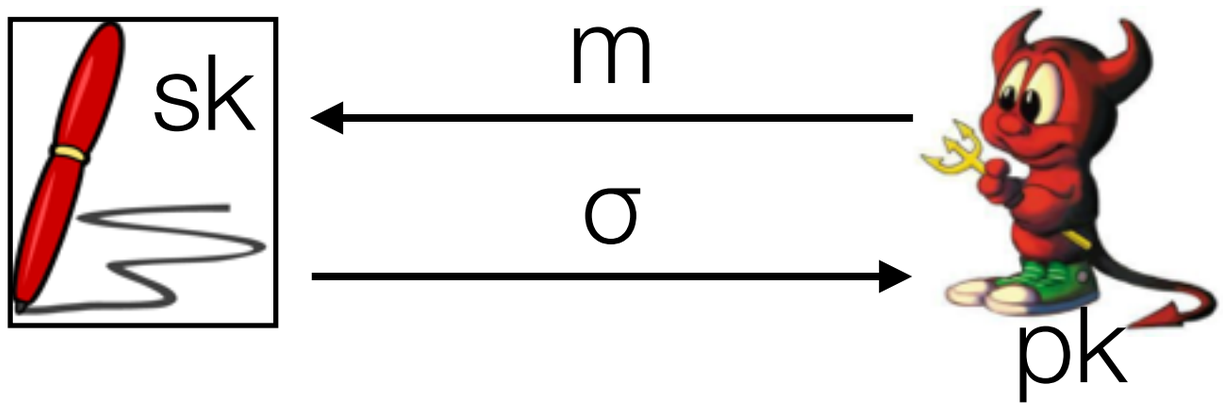

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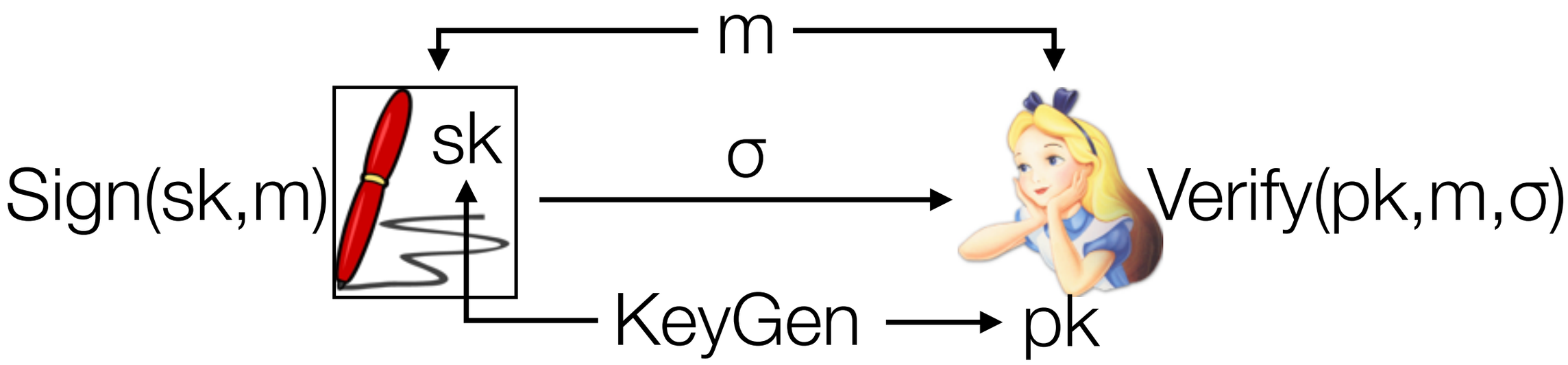

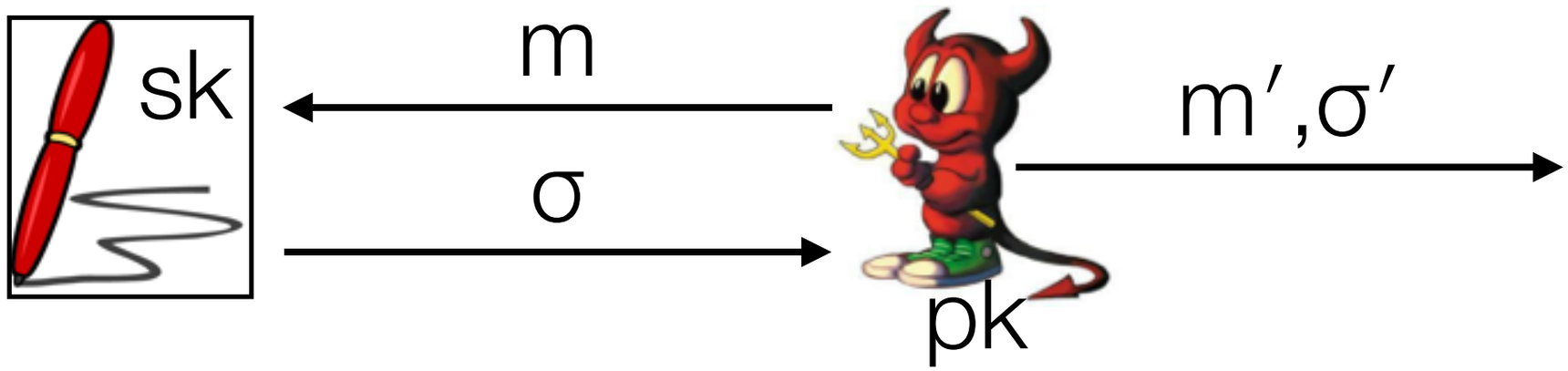

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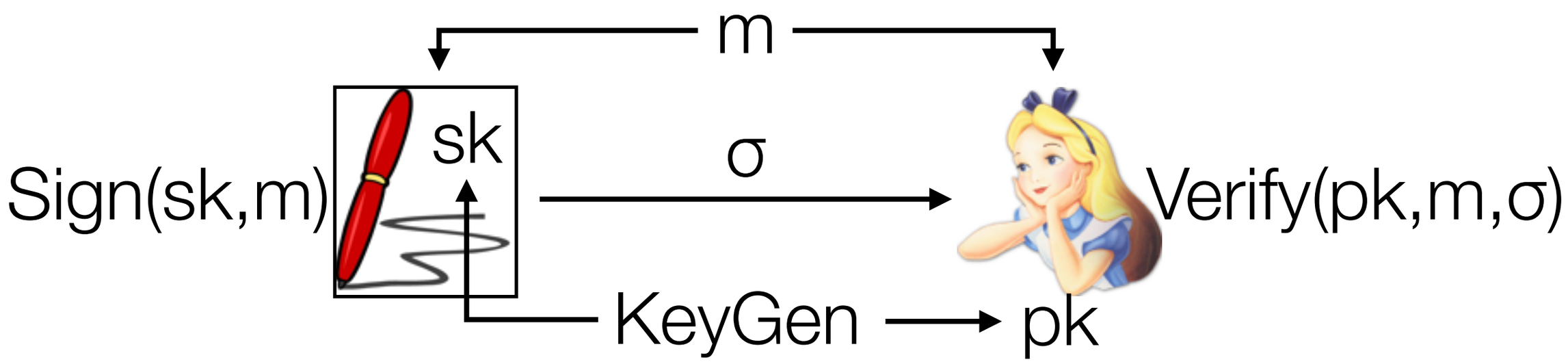

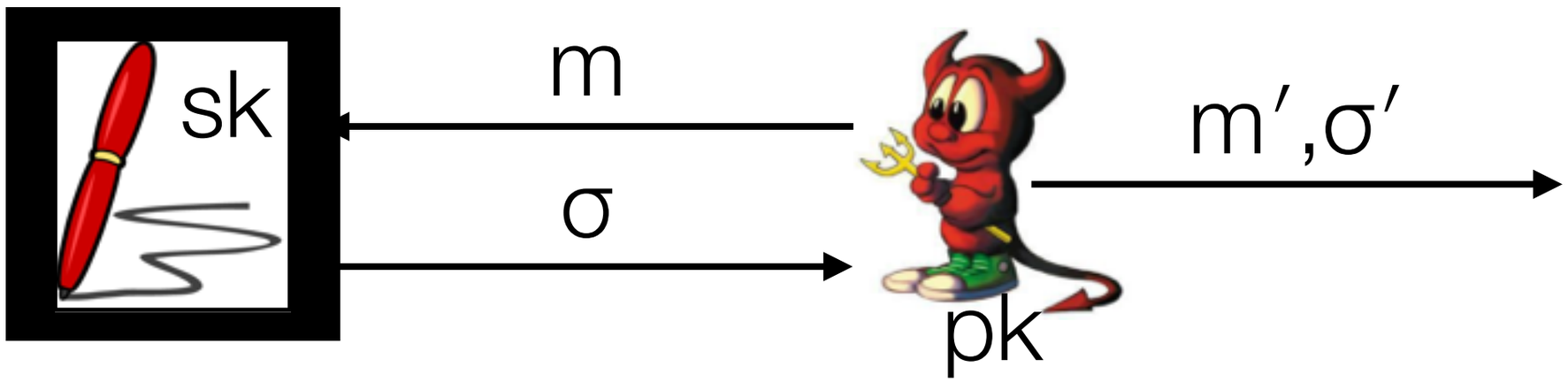

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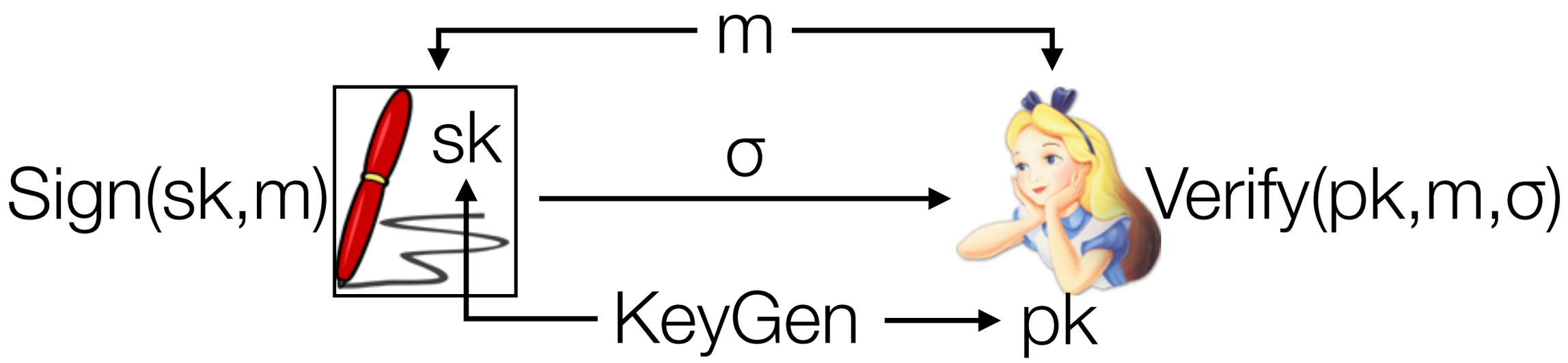

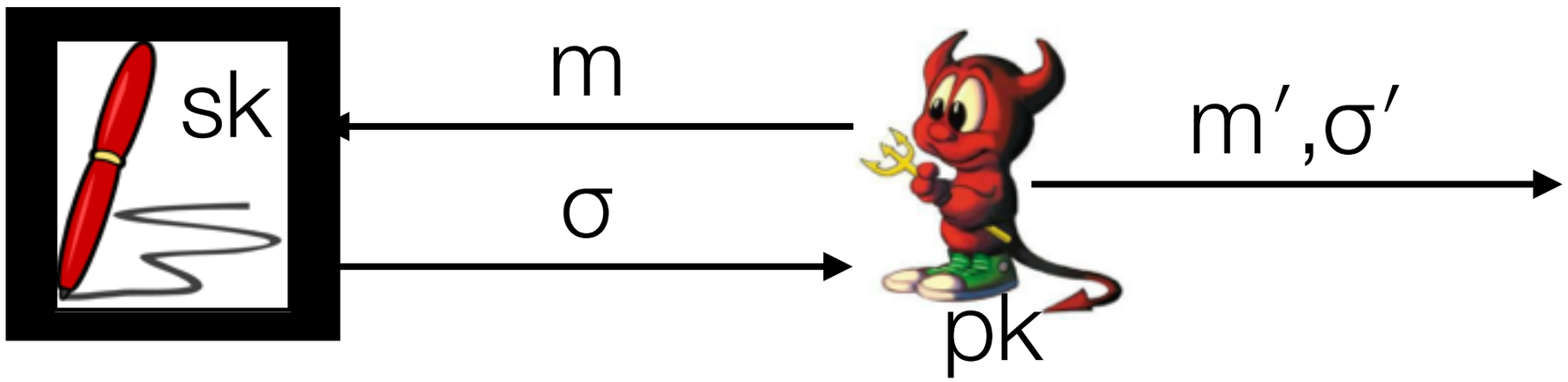

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Problem: This assumption is violated by tampering [AK96,…], side channels [W91,KJJ99,…] and fault injection [BS97,BdML97,…]

Related key attacks (RKA)

Attack on RSA-CRT [BdML97,L97] factors N given one faulty signature (attack also applies to Rabin signatures, and general RSA)

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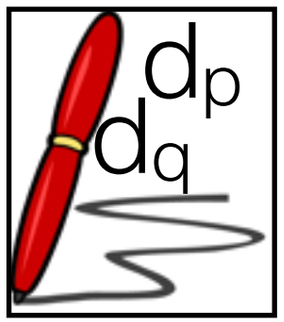

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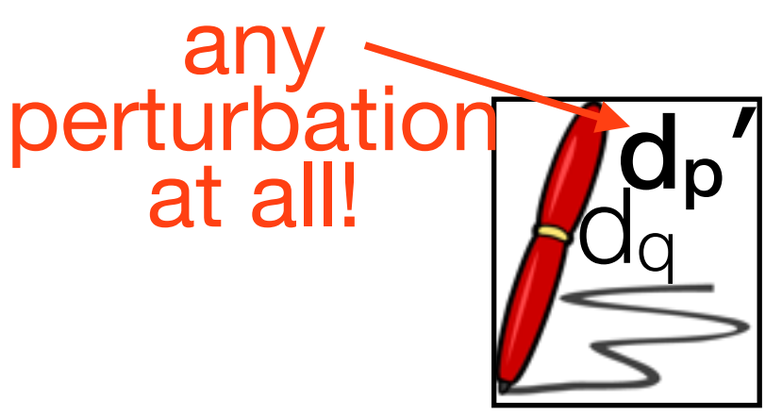

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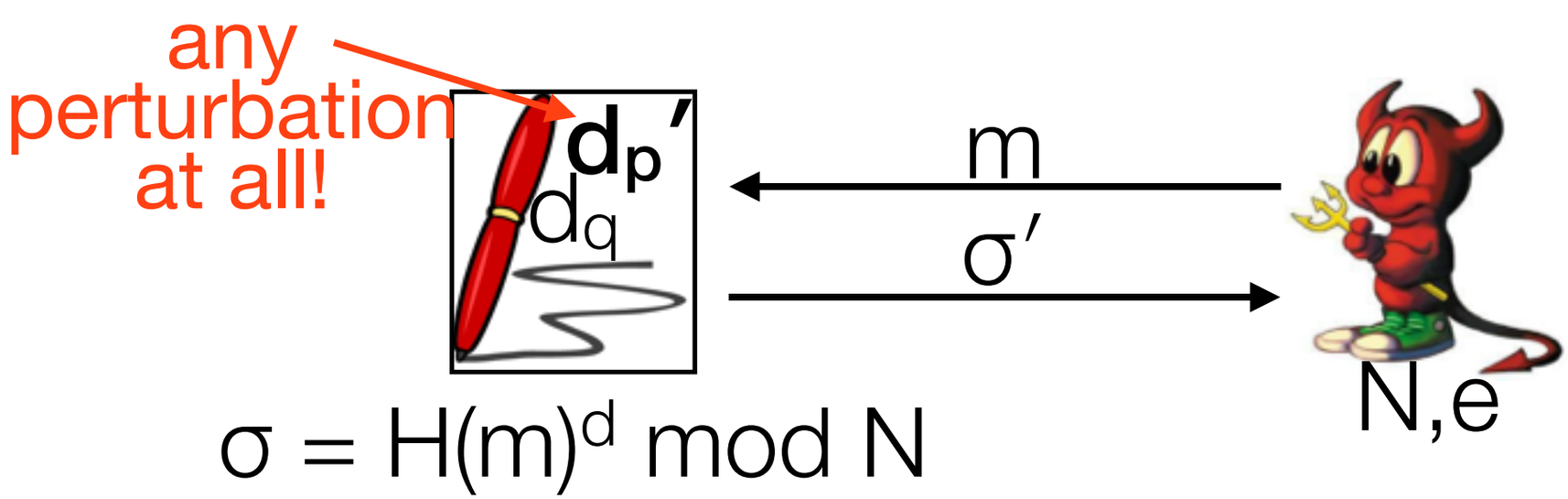

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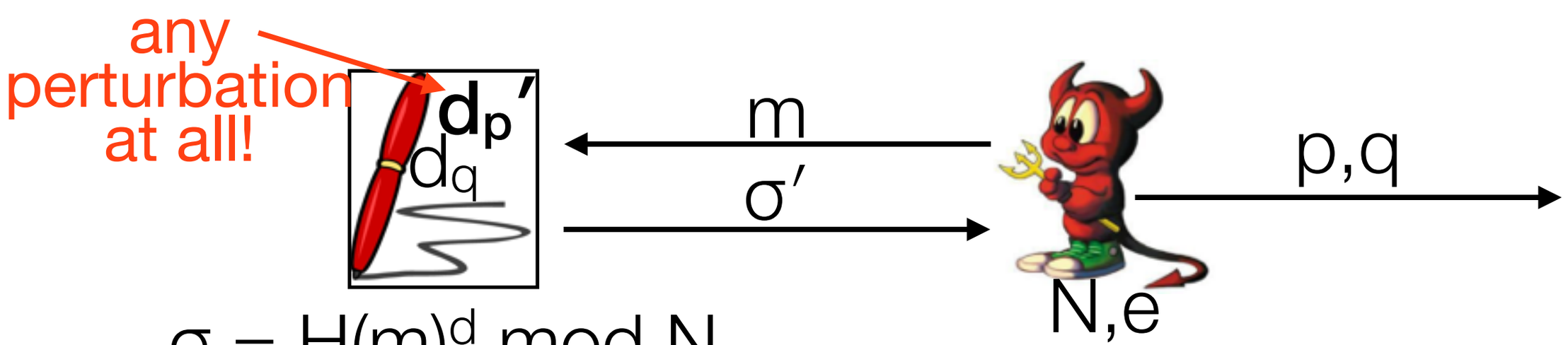

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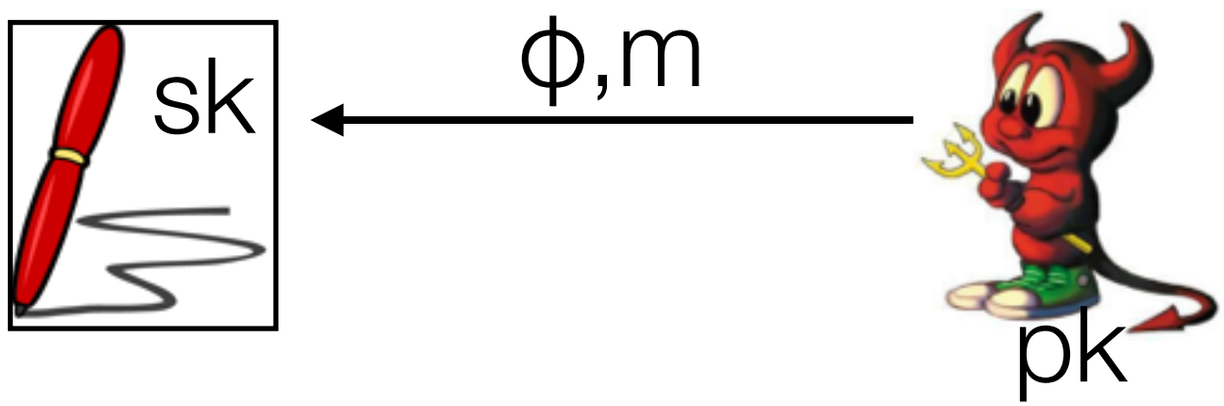

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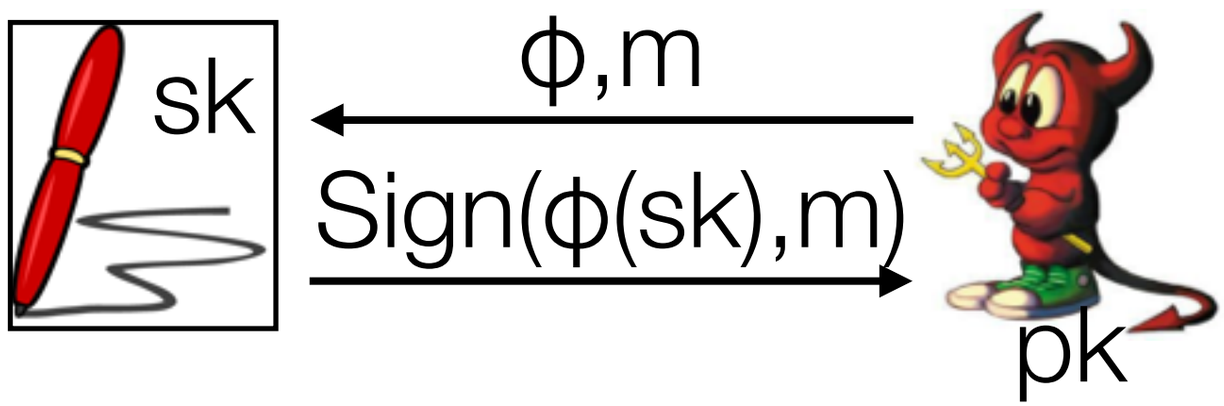

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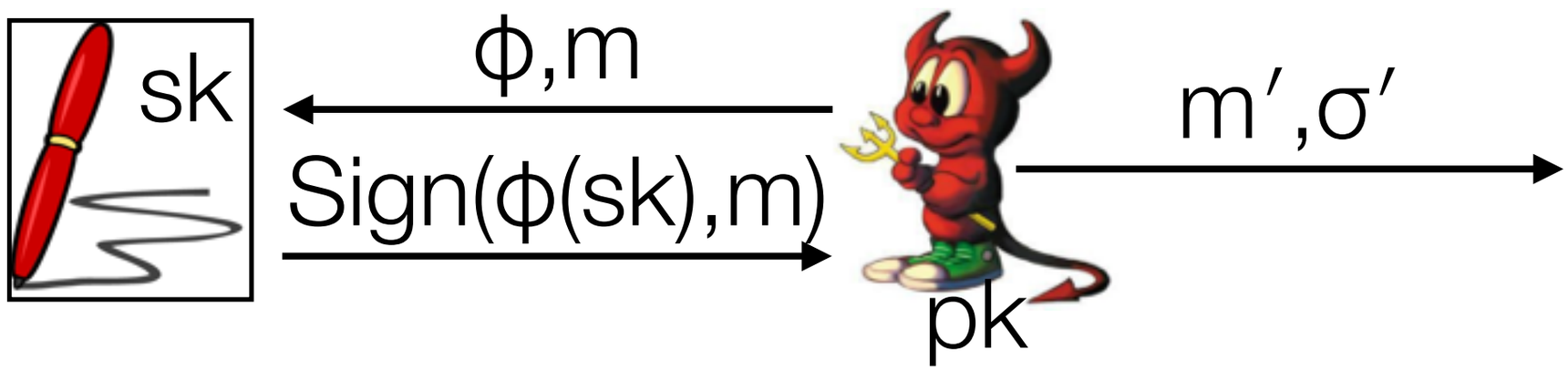

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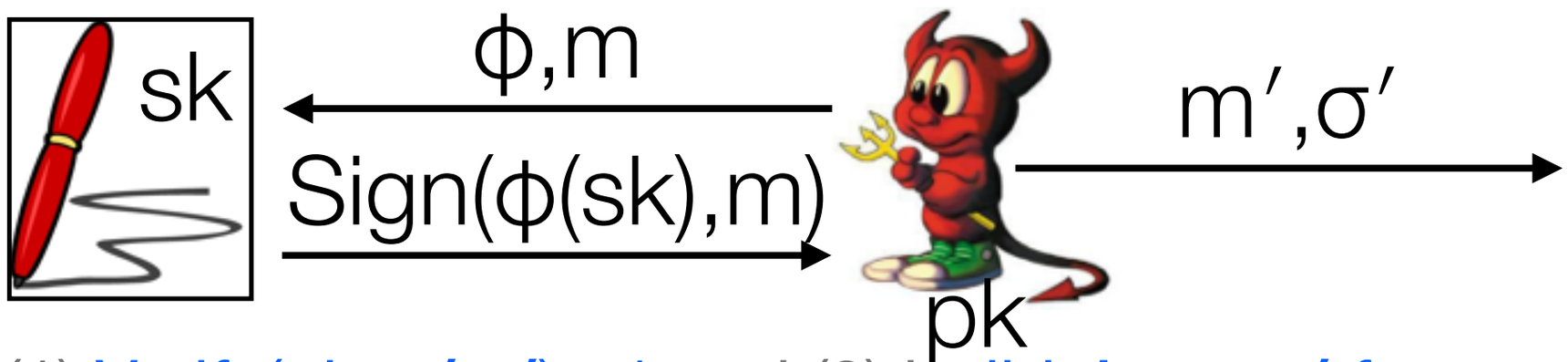

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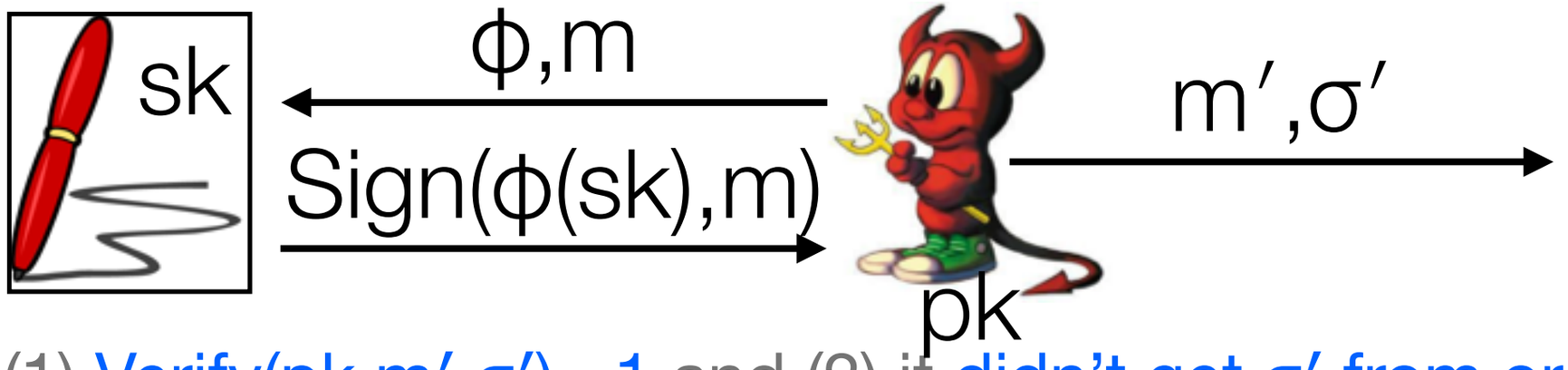

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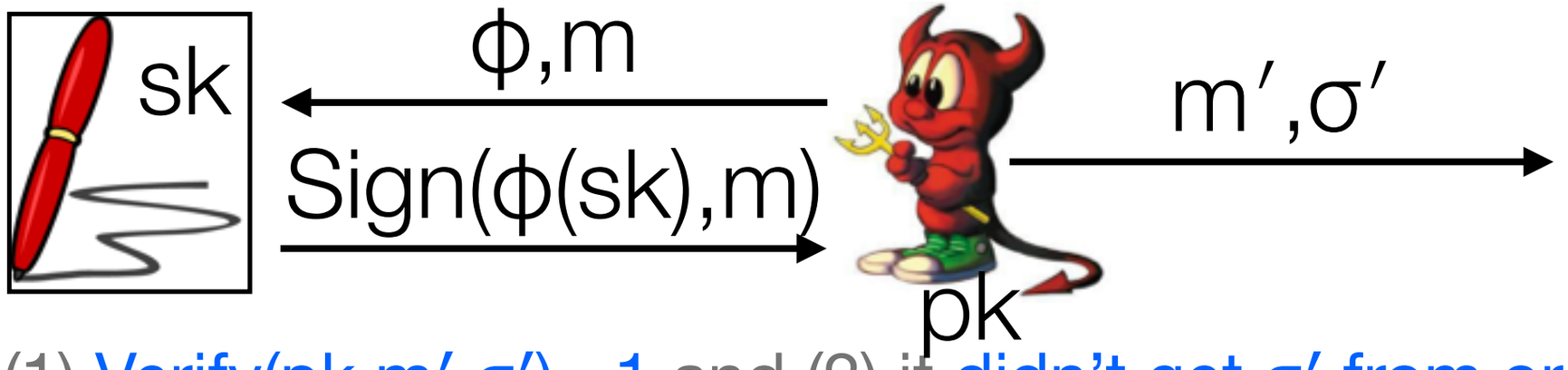

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Φ={all functions} isn't possible [BK03]

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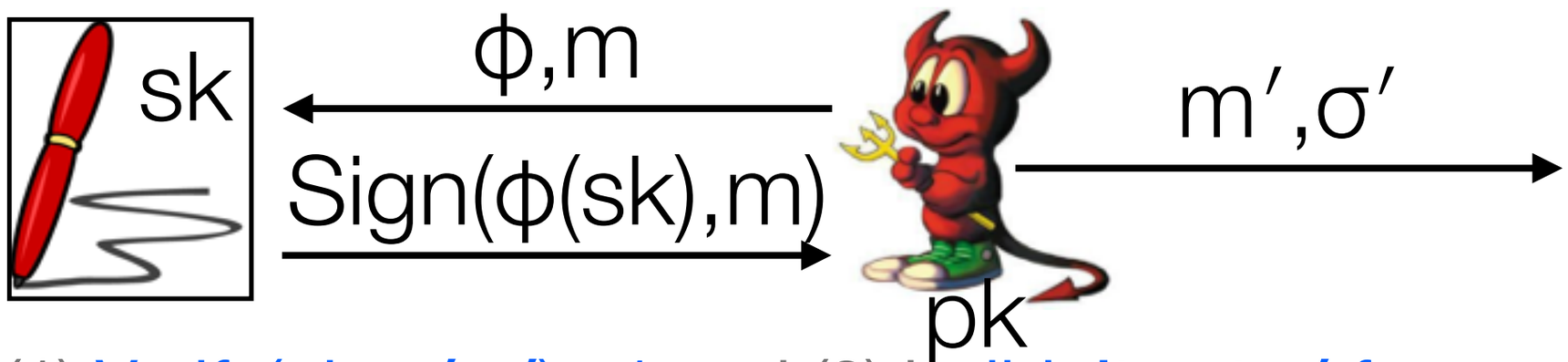

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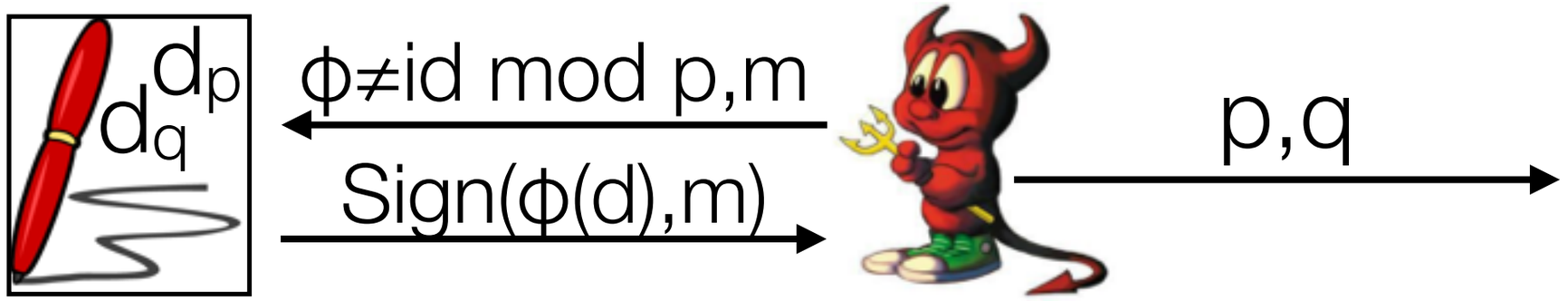

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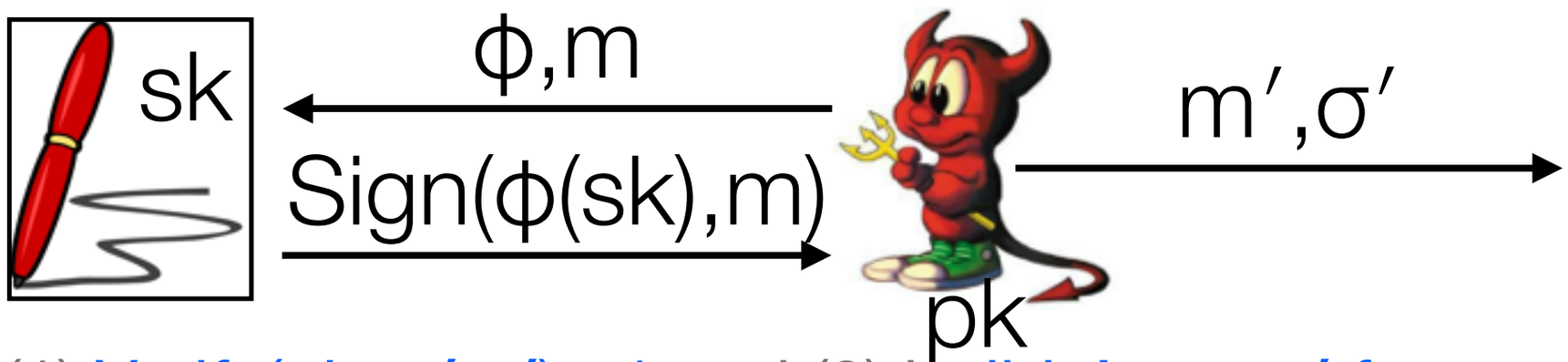

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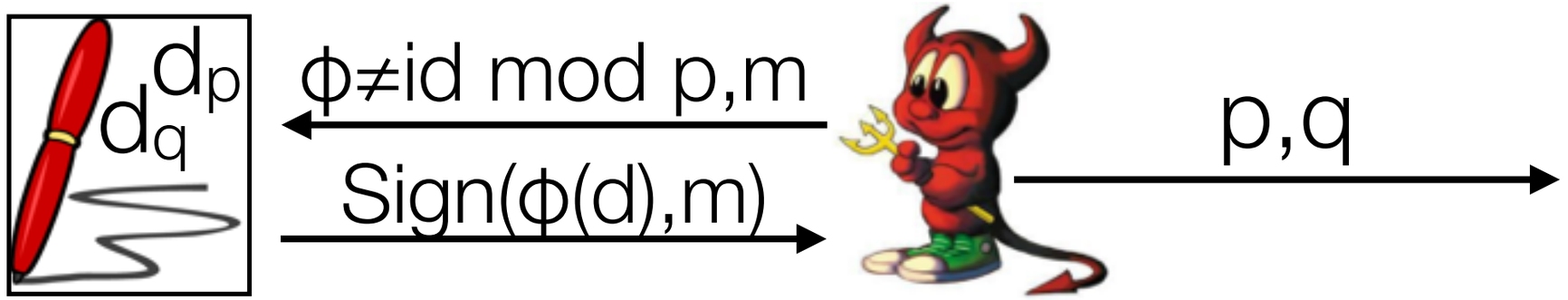

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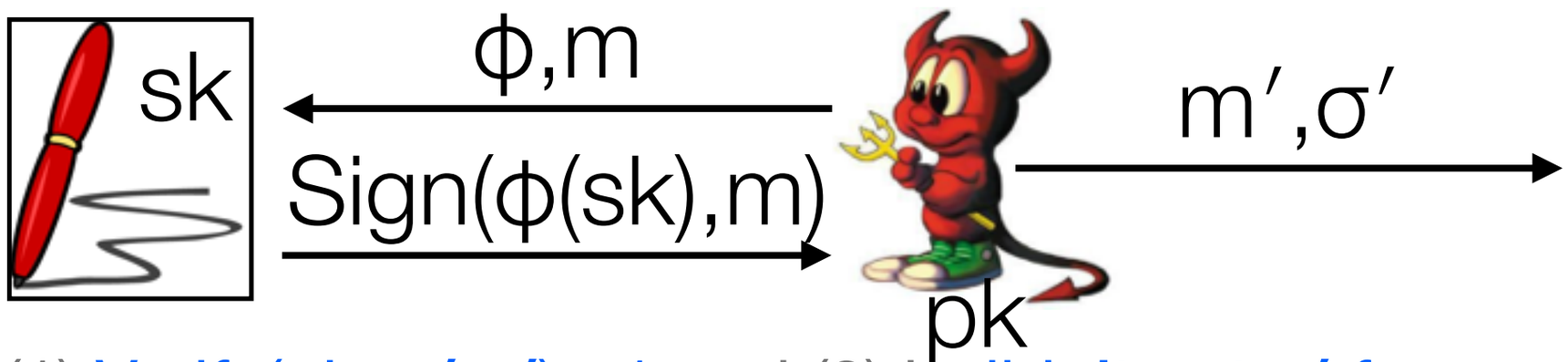

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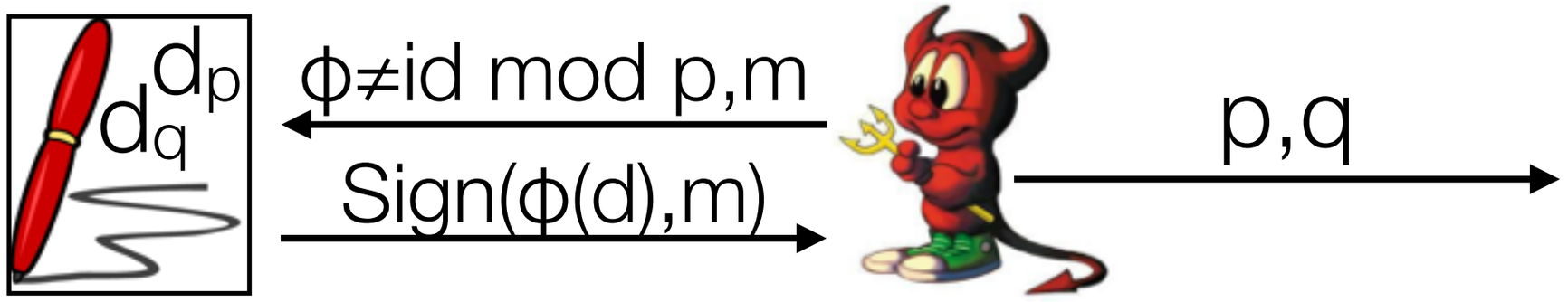

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Problem: ϕ-RKA schemes are really hard to construct
(for interesting classes ϕ; for most primitives)

Our construction [Bellare **M** Thomson Eurocrypt14]

ϕ-RKA-OWF

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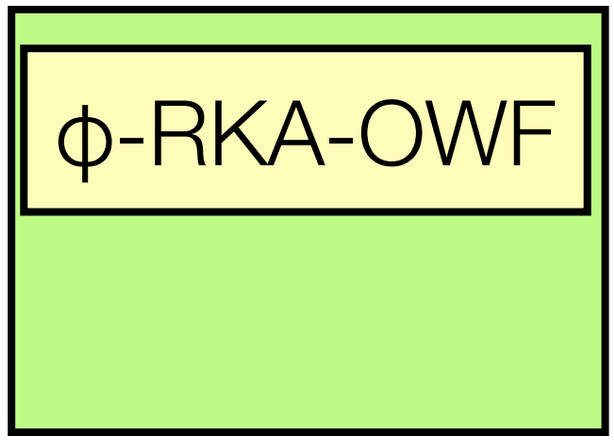

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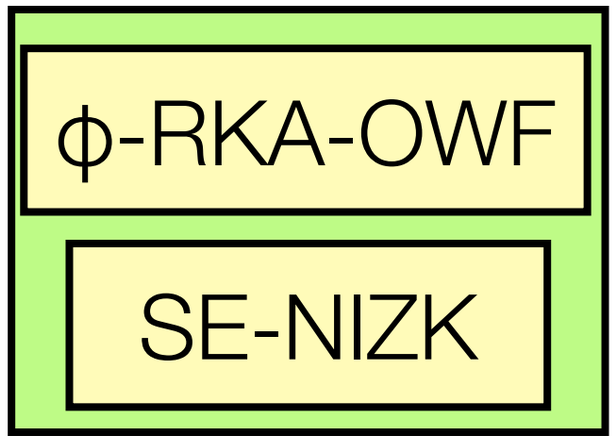

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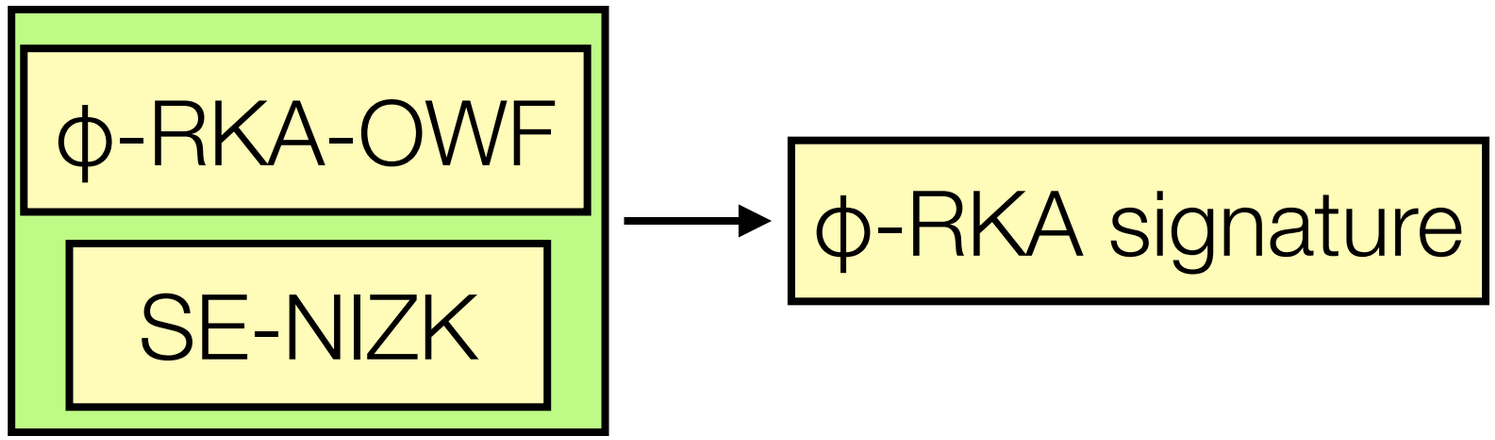

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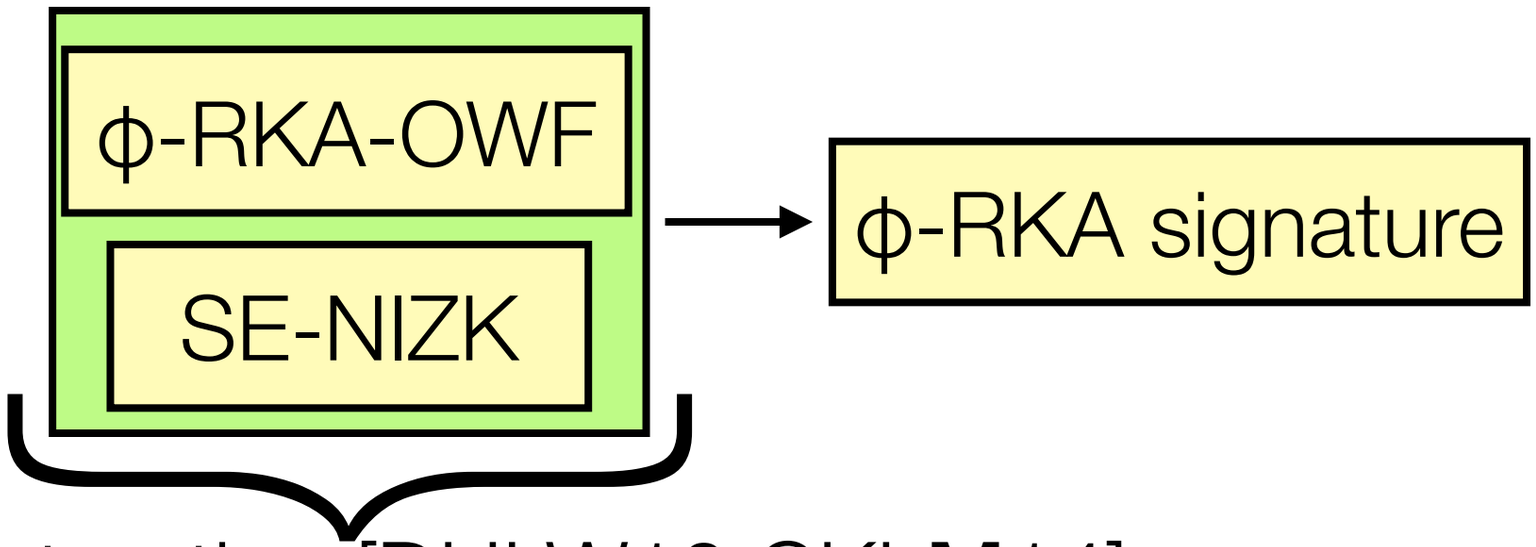

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- KeyGen: crs←CRSGen; x←Dom(f); y←f(x)
  return (pk=(crs,y),sk=x)
- Sign(sk,m): return Prove(crs,y||m,x)
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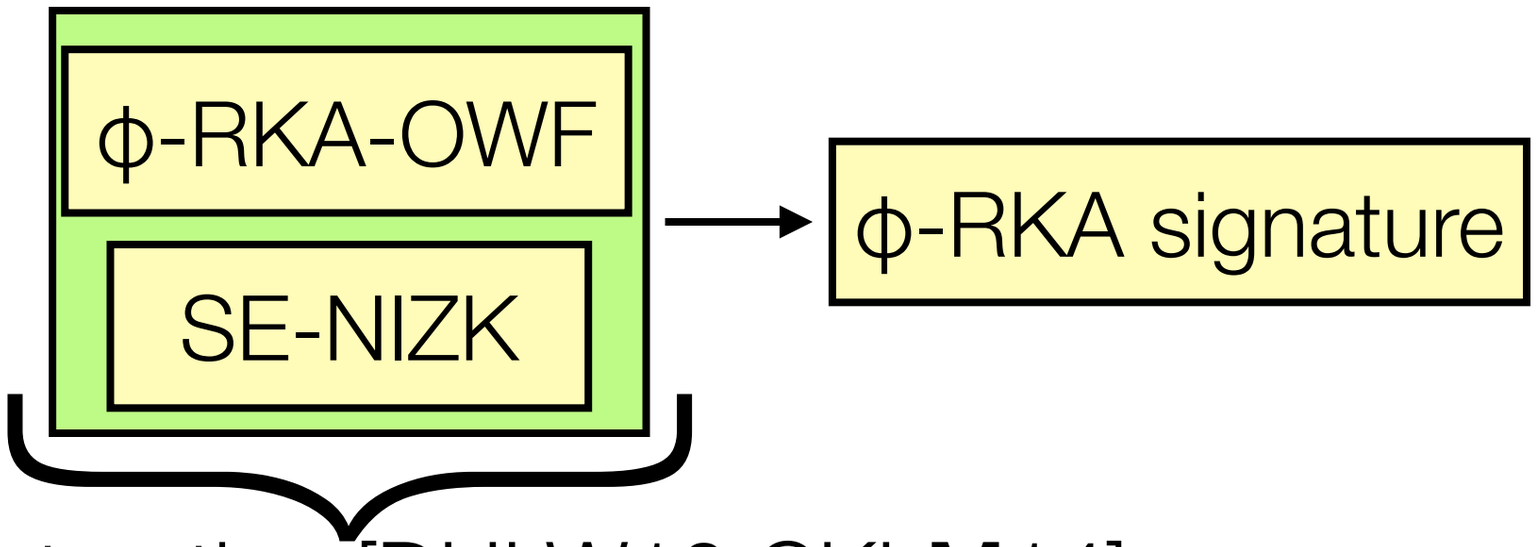

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proof of knowledge of secret key

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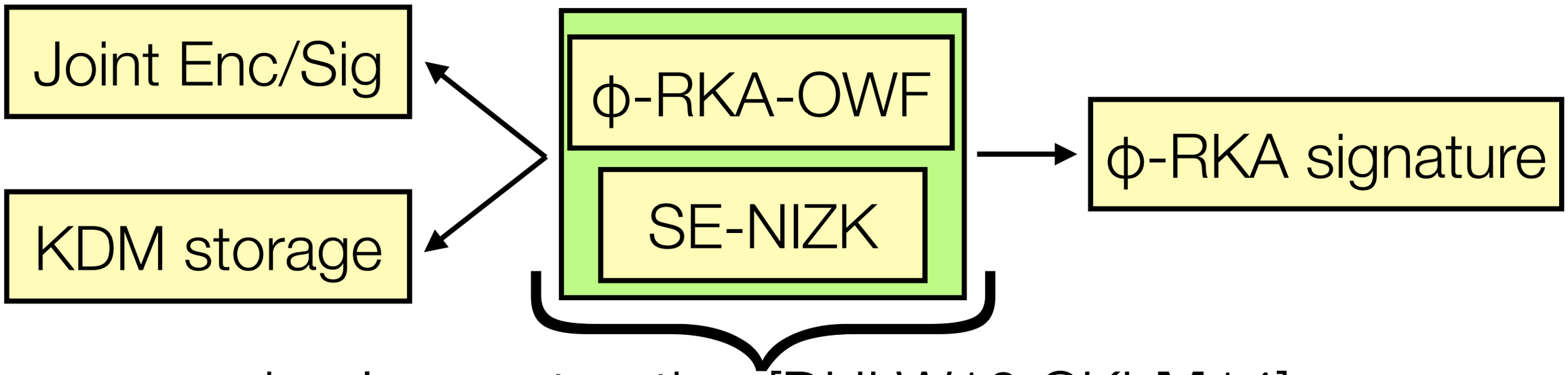

simple construction [DHLW10,CKL**M**14]

- KeyGen: crs←CRSGen; x←Dom(f); y←f(x)
  return (pk=(crs,y),sk=x)
- Sign(sk,m): return Prove(crs,y||m,x)
- Verify(pk,σ,m): return Verify(crs,y||m,σ)

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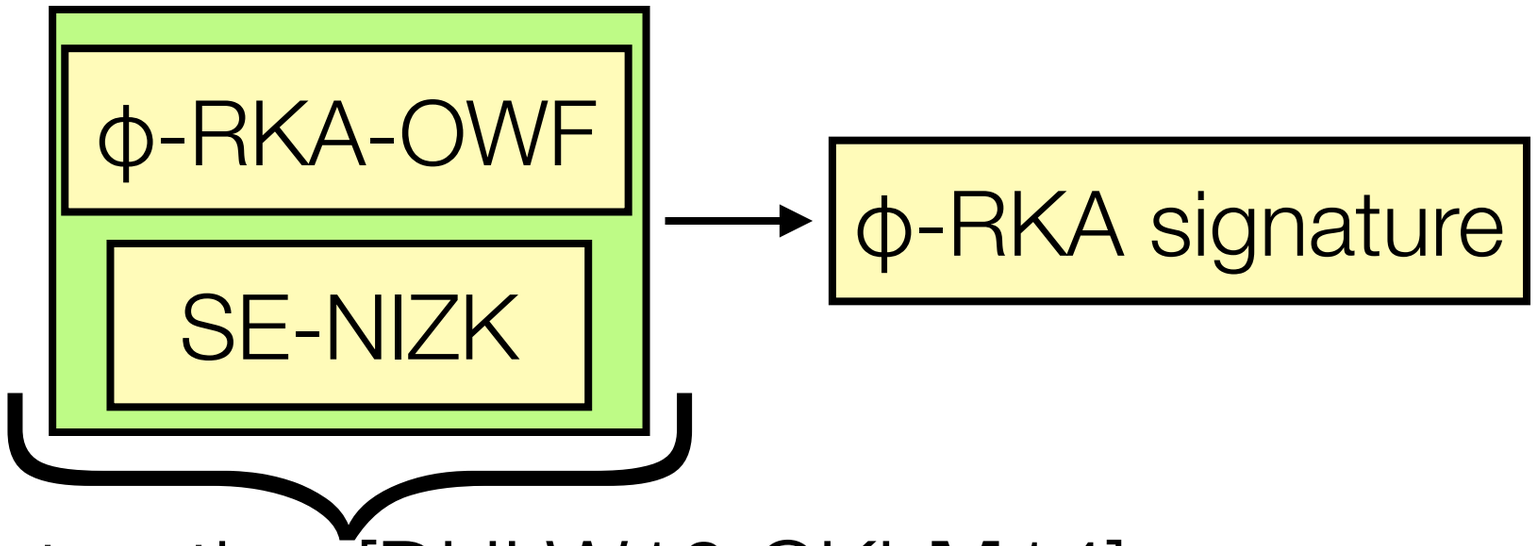

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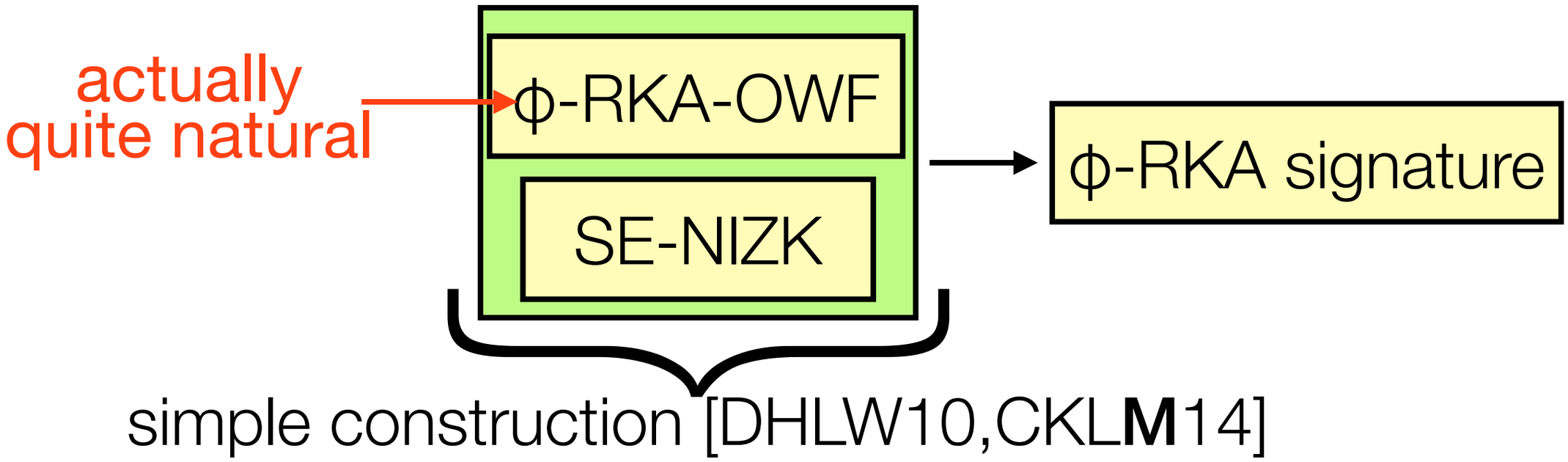

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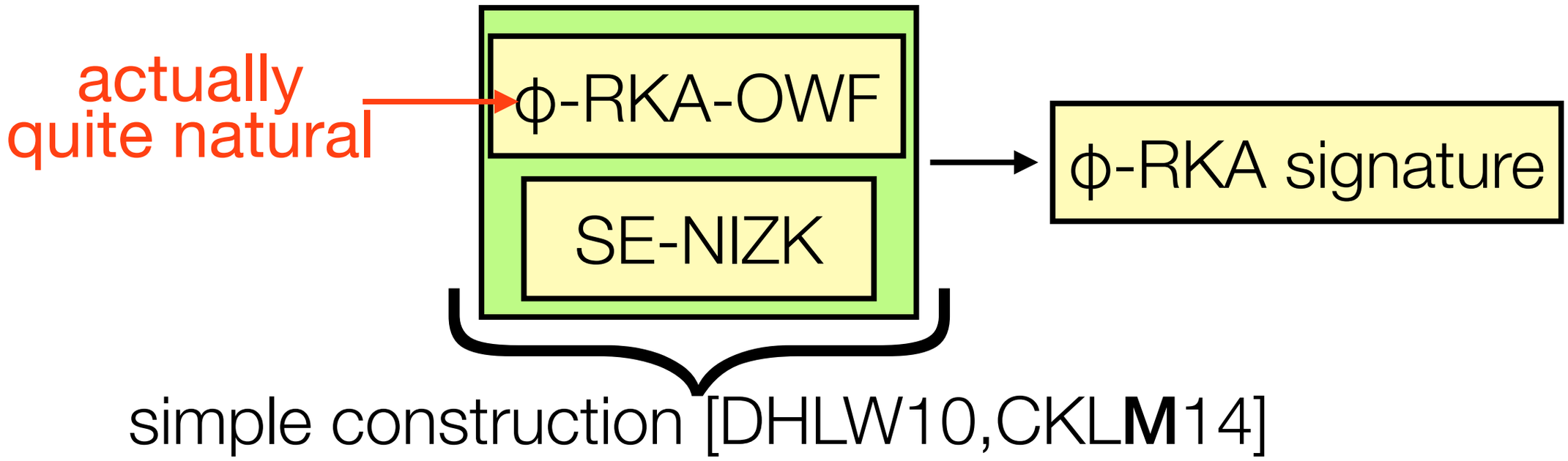

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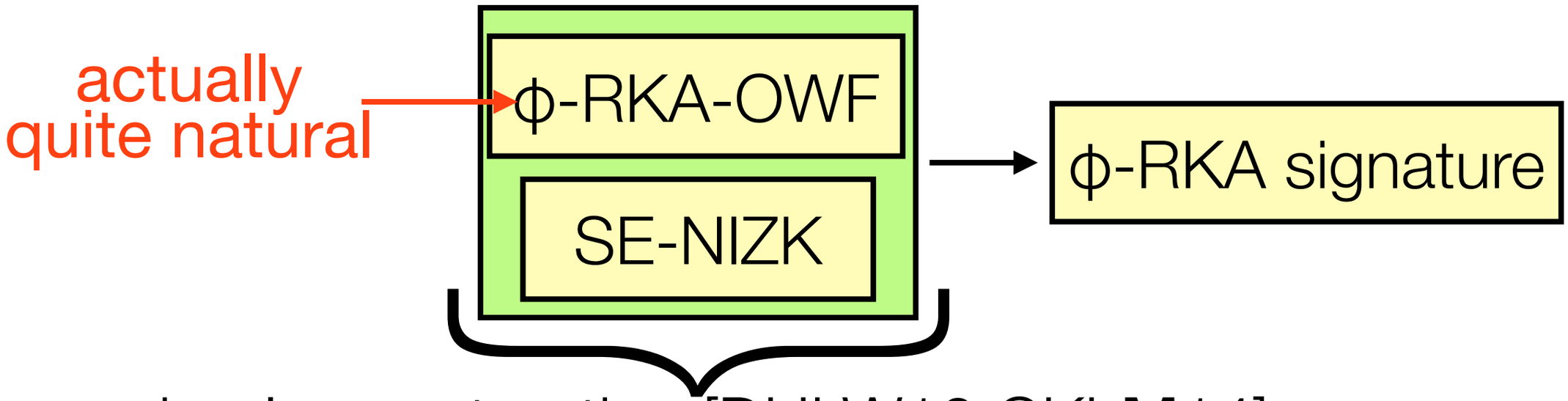

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Creating new RKA-secure signatures is easier!

Takeaway

Problem: ϕ-RKA schemes are really hard to construct
(for interesting classes ϕ; for most primitives)

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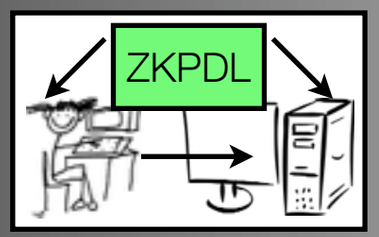
Our result can pave the way for easier RKA constructions

My research

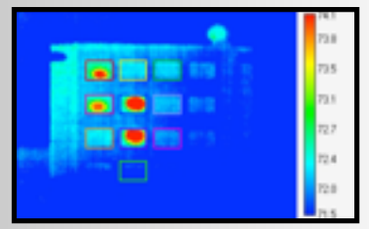

[**M**SF10,L**M**13]

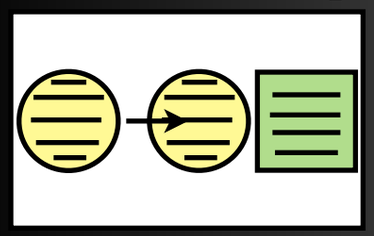

[B**M**T14]

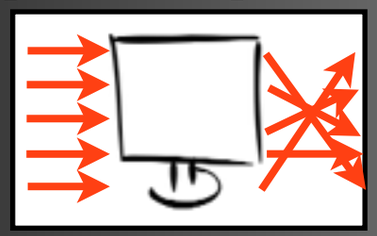


[**M**EKHL10]

[**M**MCS11]


[M**M**S11]


[C**M**14]


[CKL**M**12,13a,13b]

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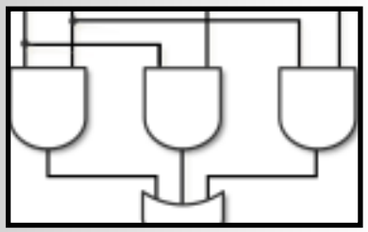
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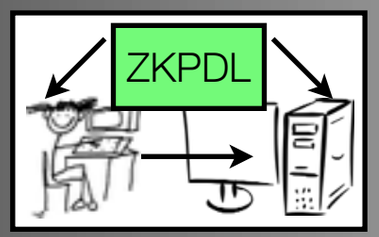

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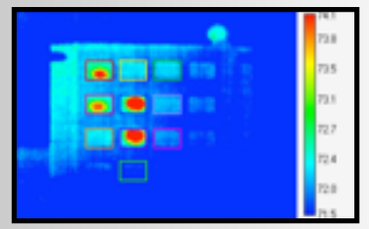
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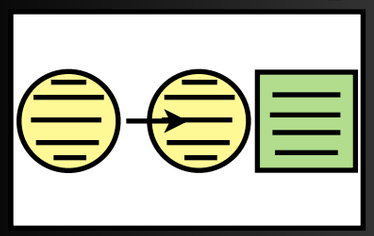
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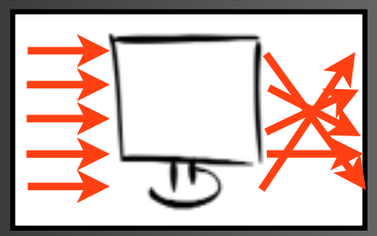
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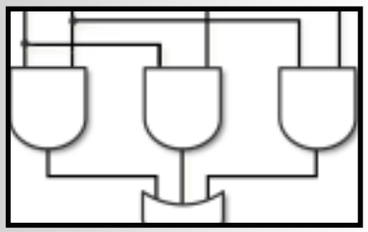
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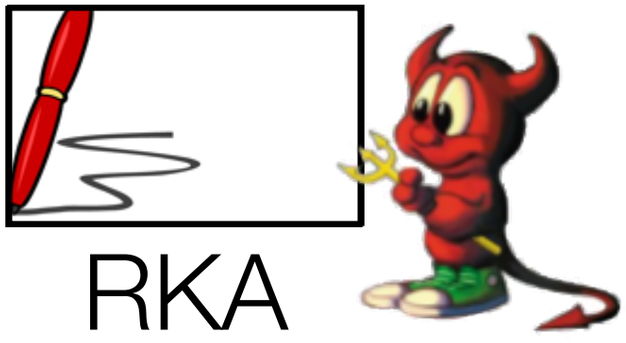

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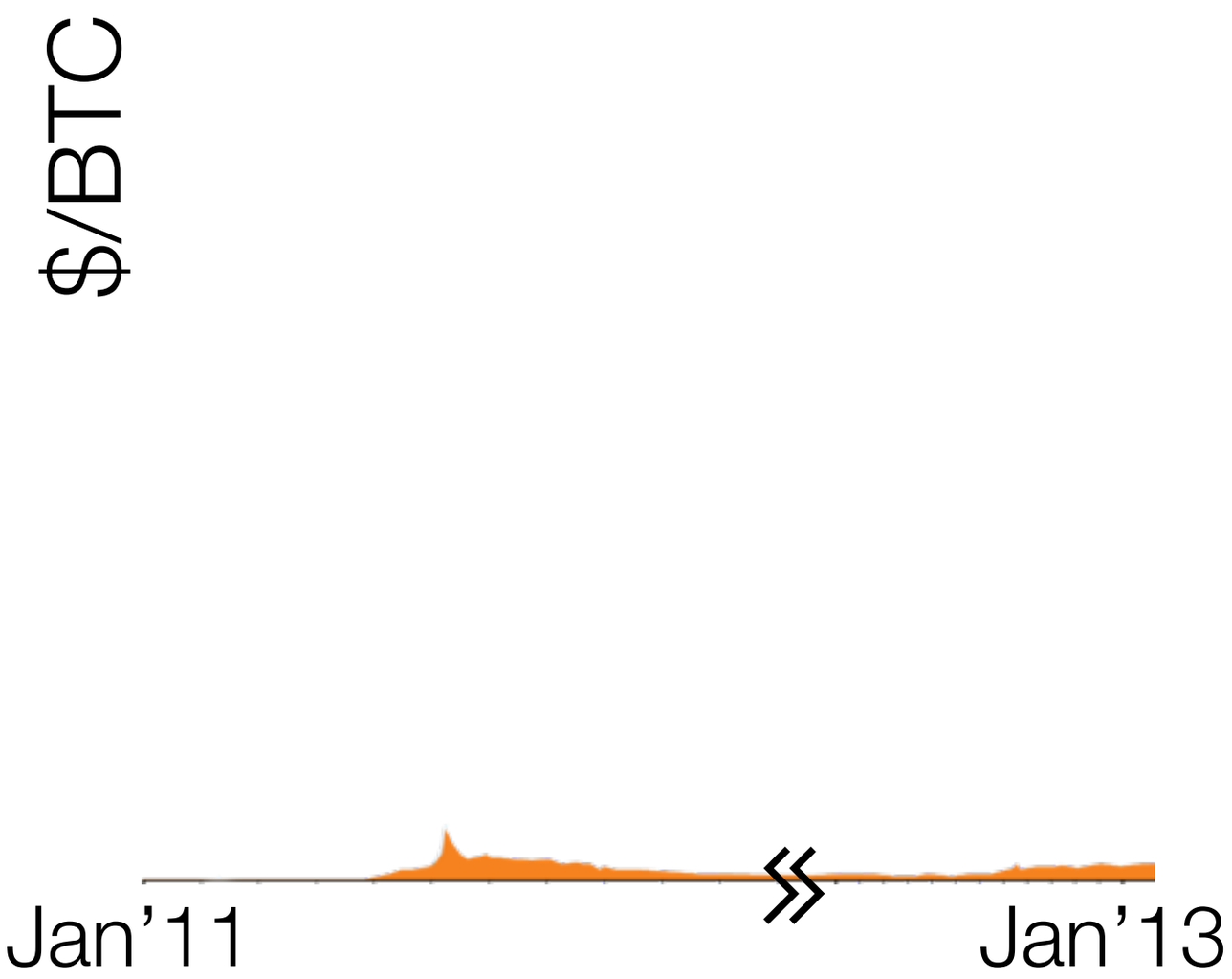
How much anonymity does Bitcoin really provide?

Bitcoin’s explosive growth



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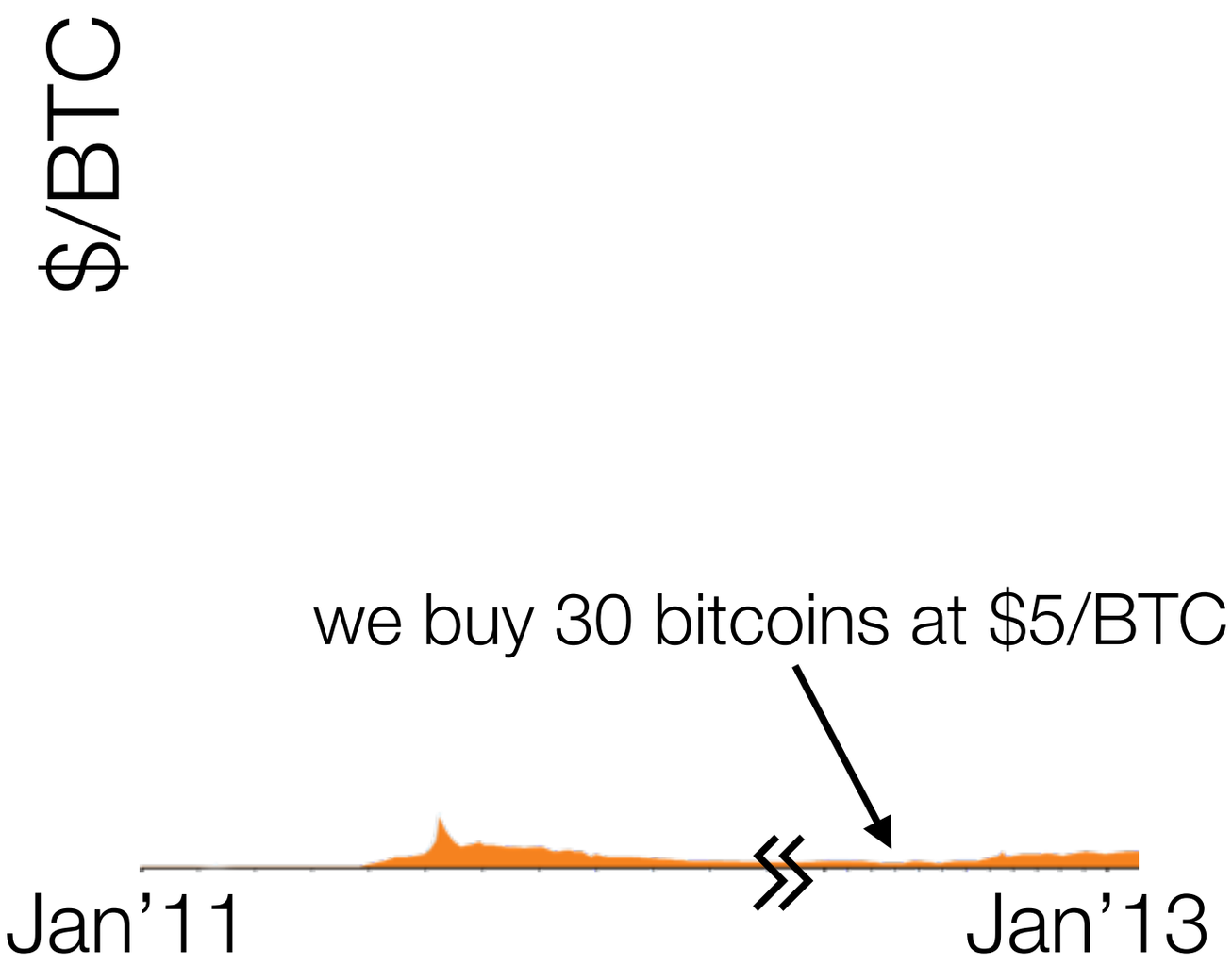

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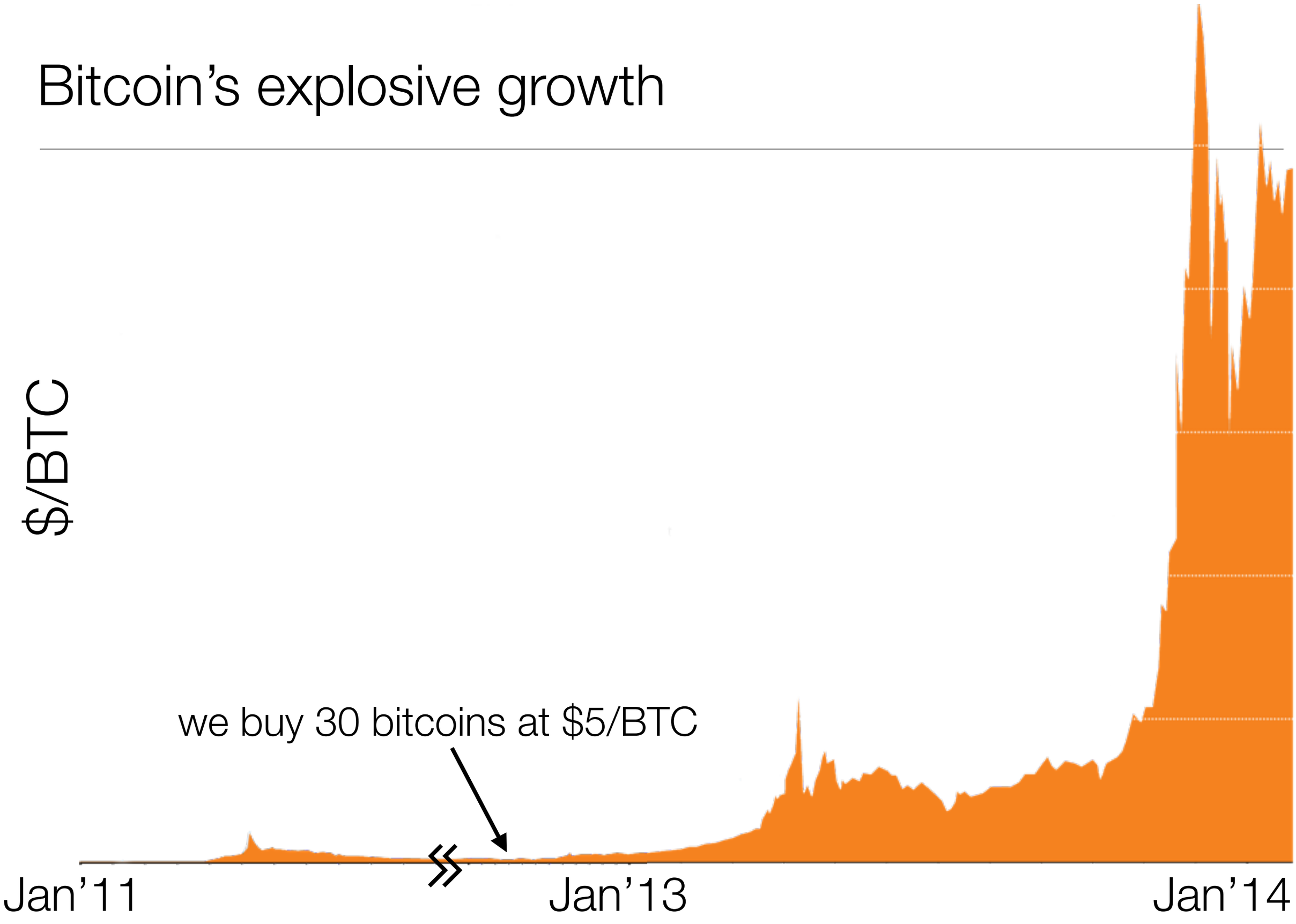

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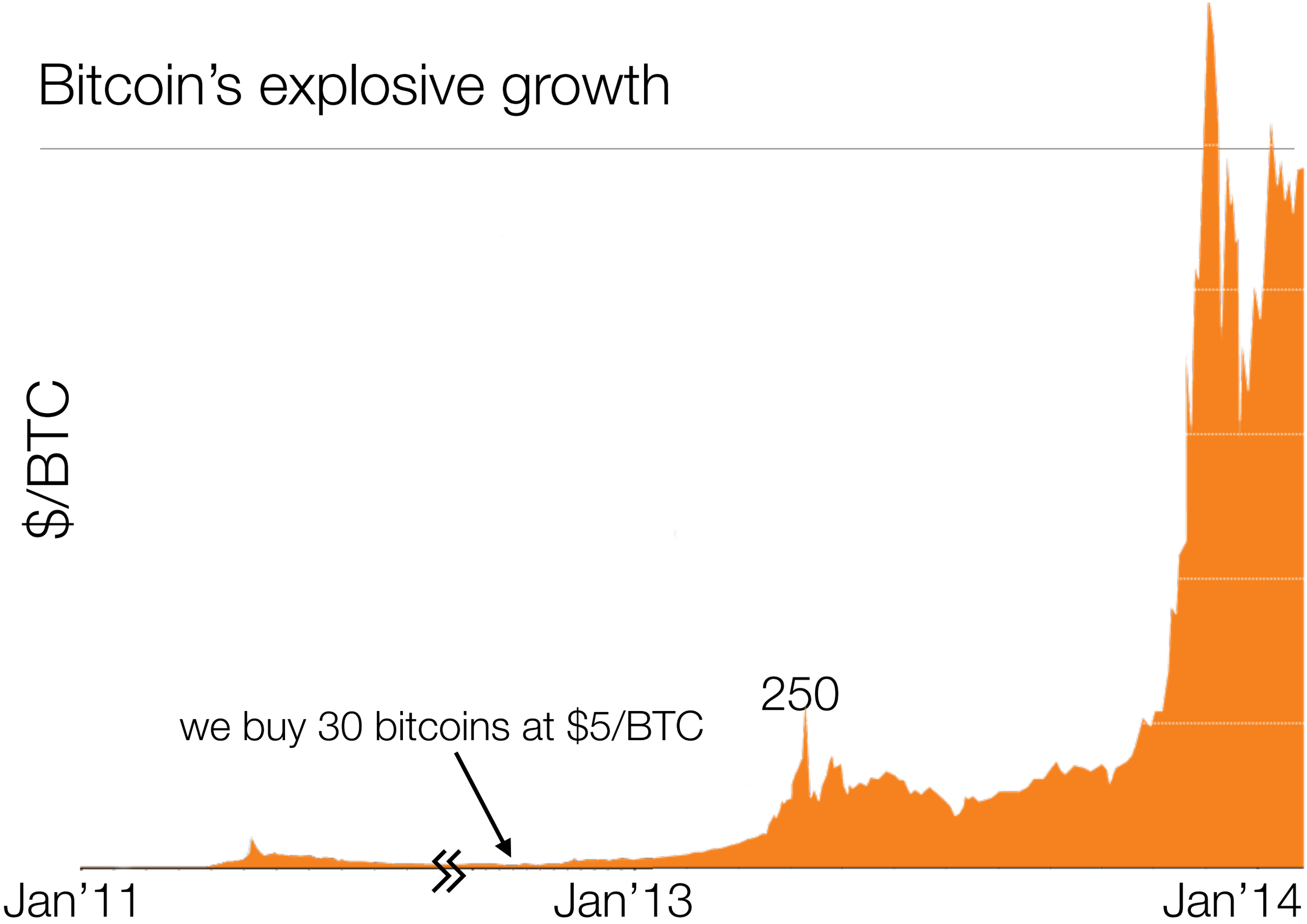

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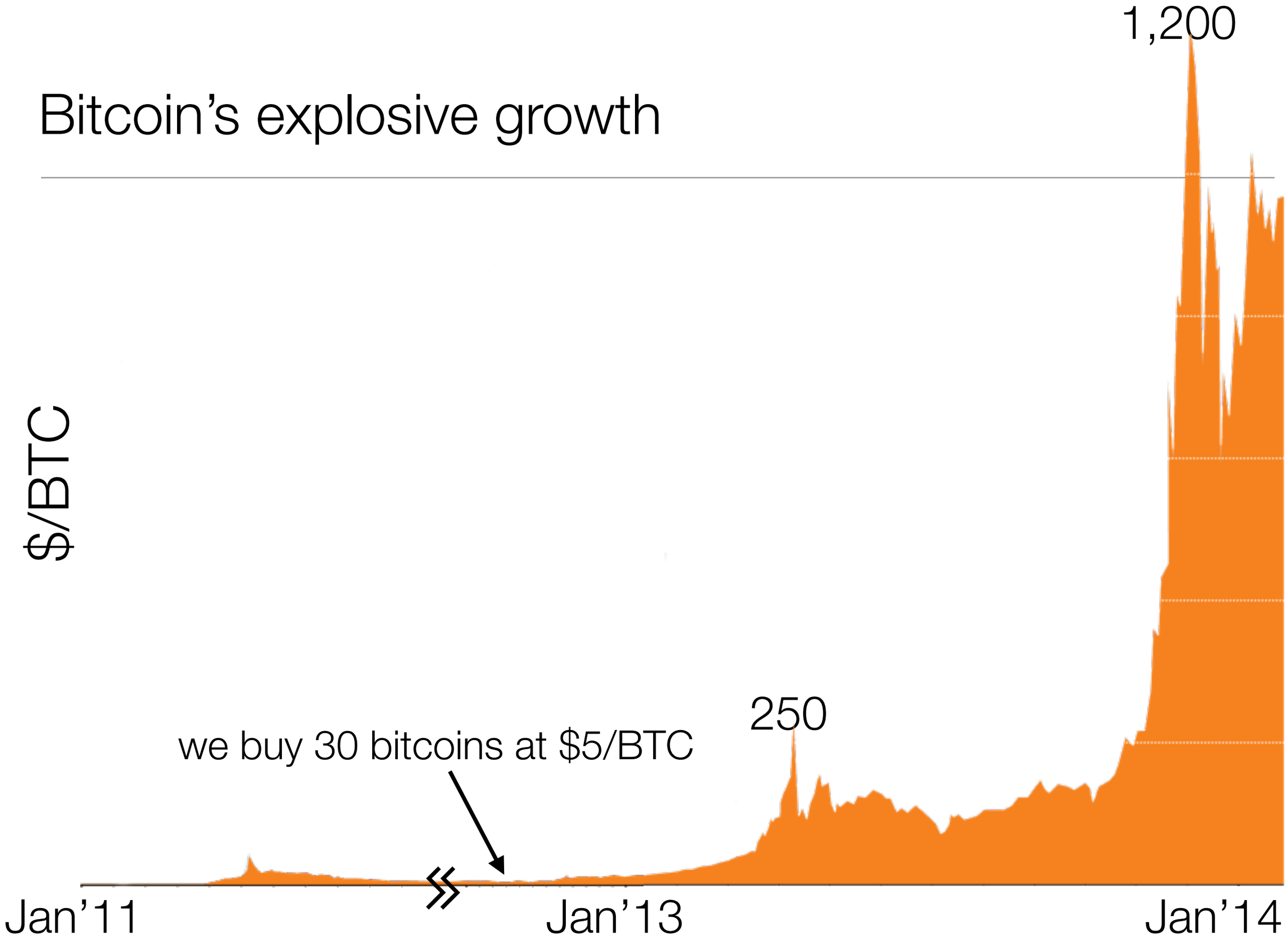

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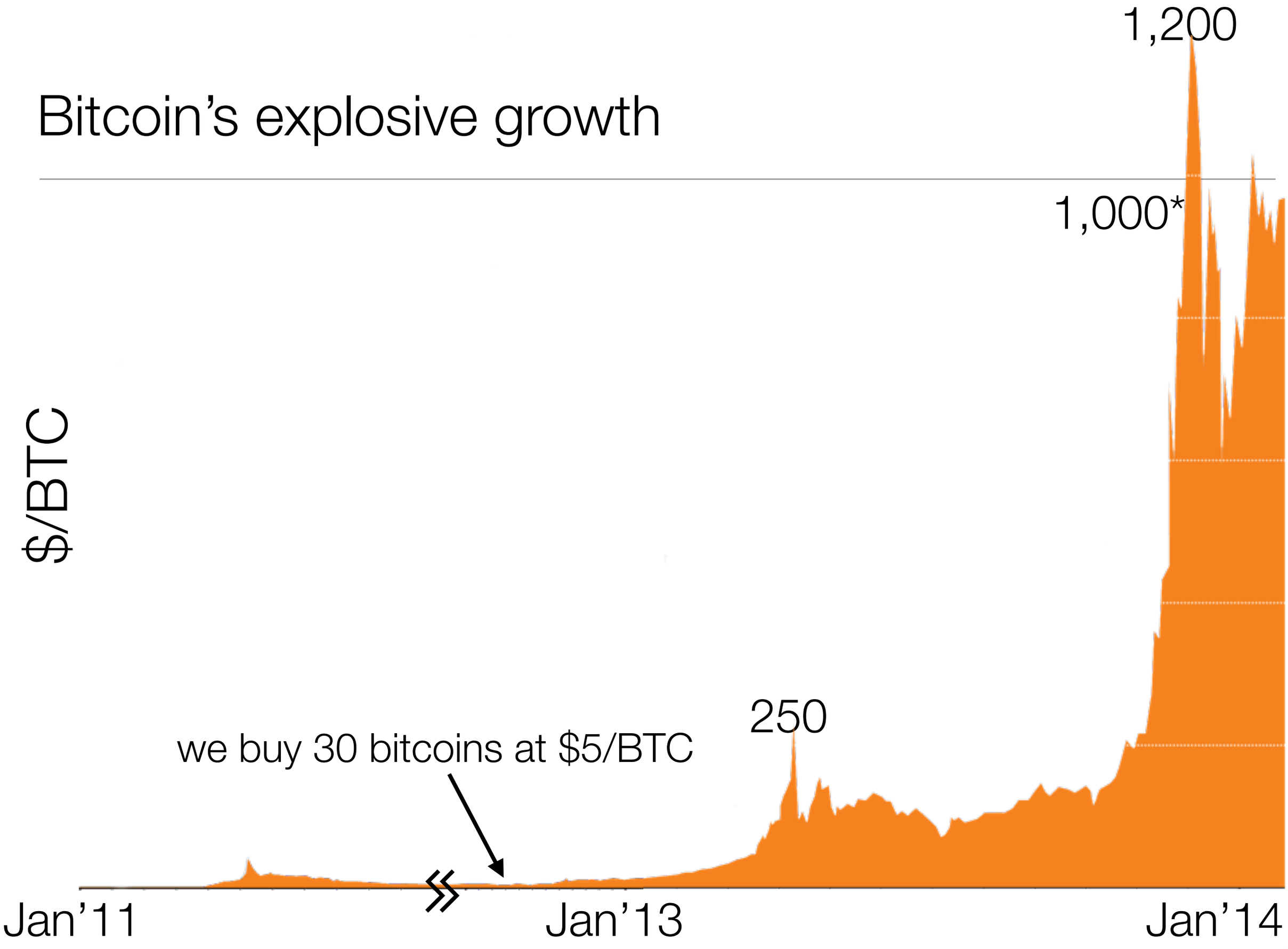

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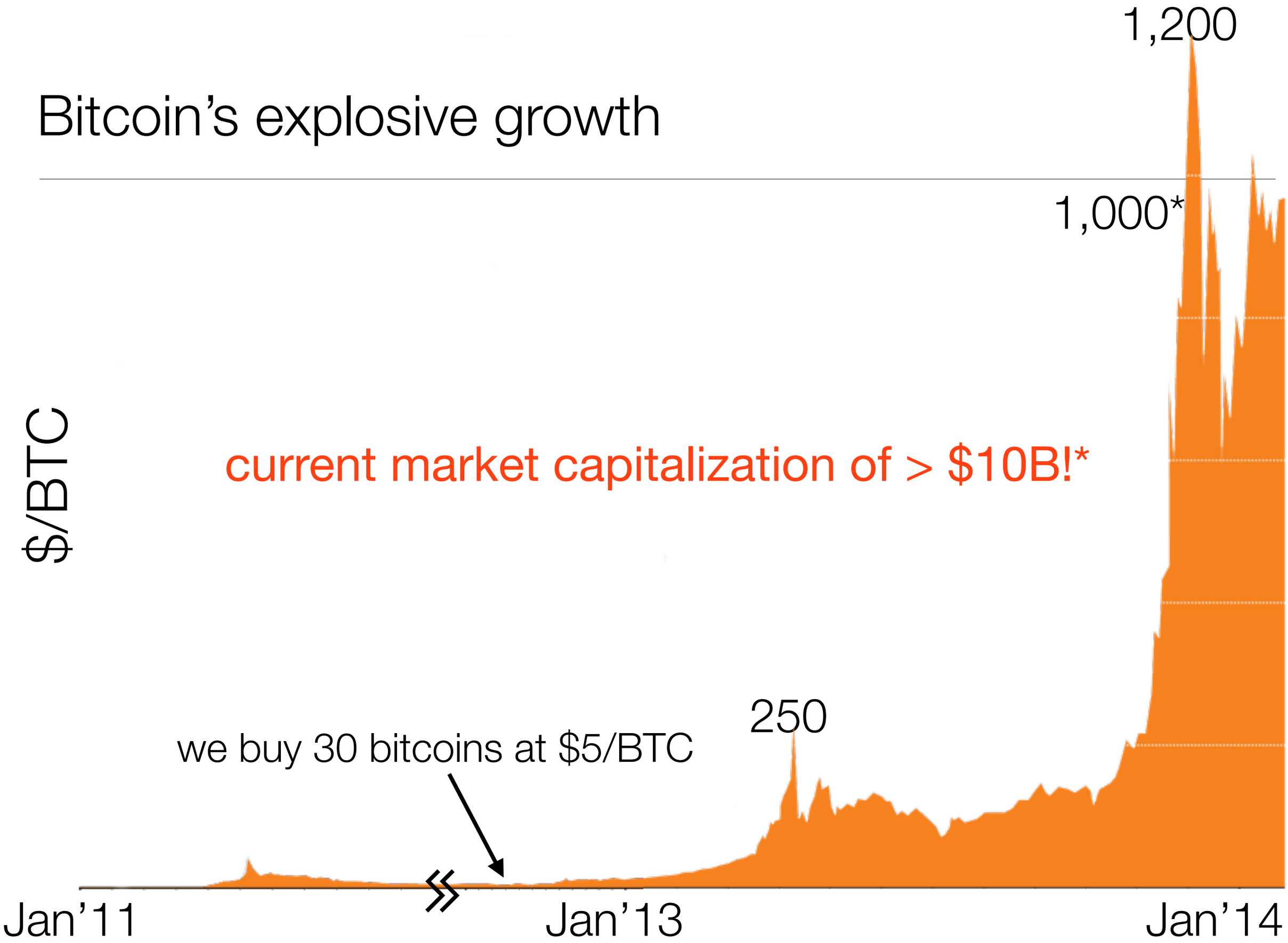

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- **decentralized**

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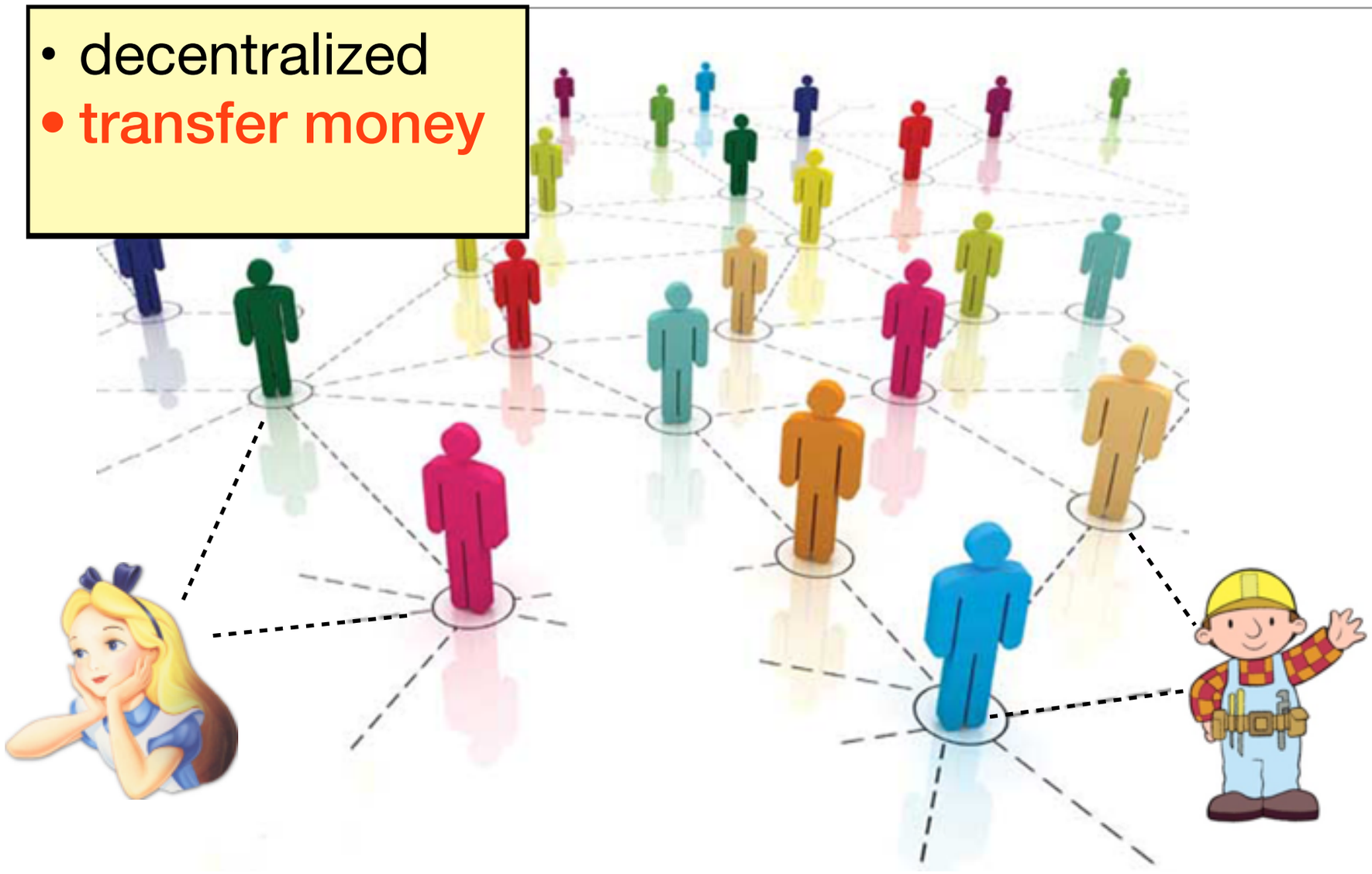
- **transfer money**



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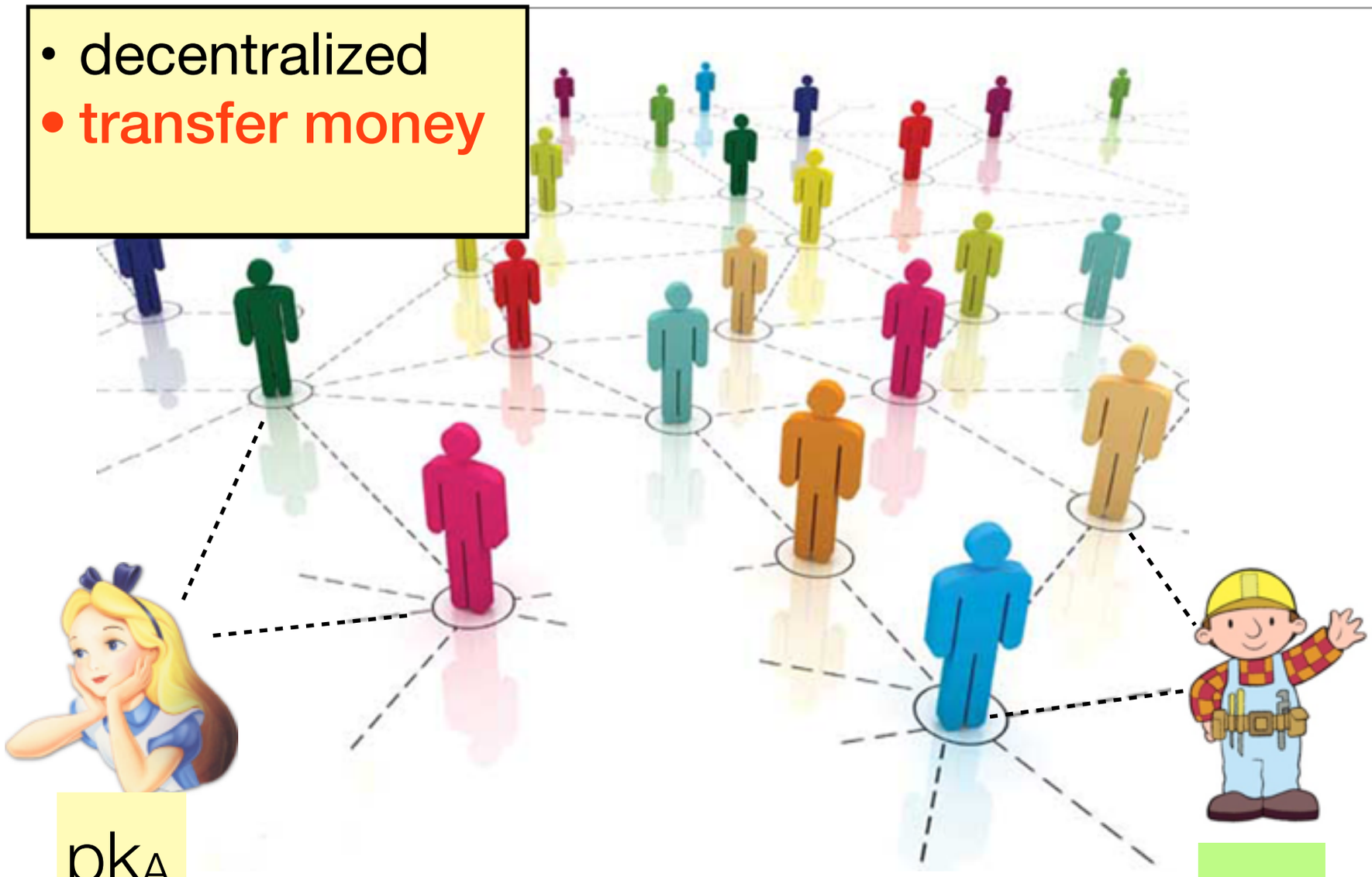

pk_A

pk_B

public key
address

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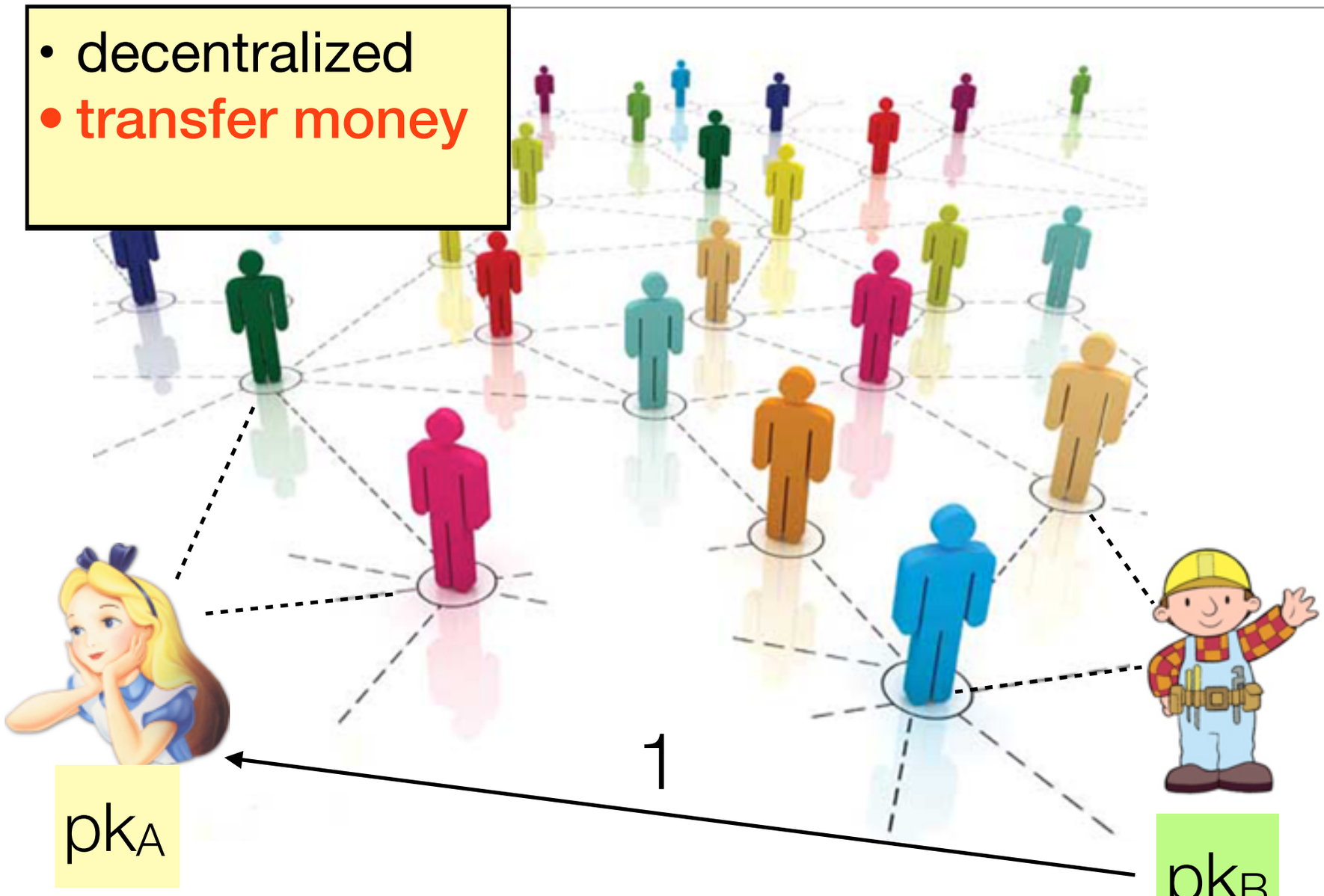

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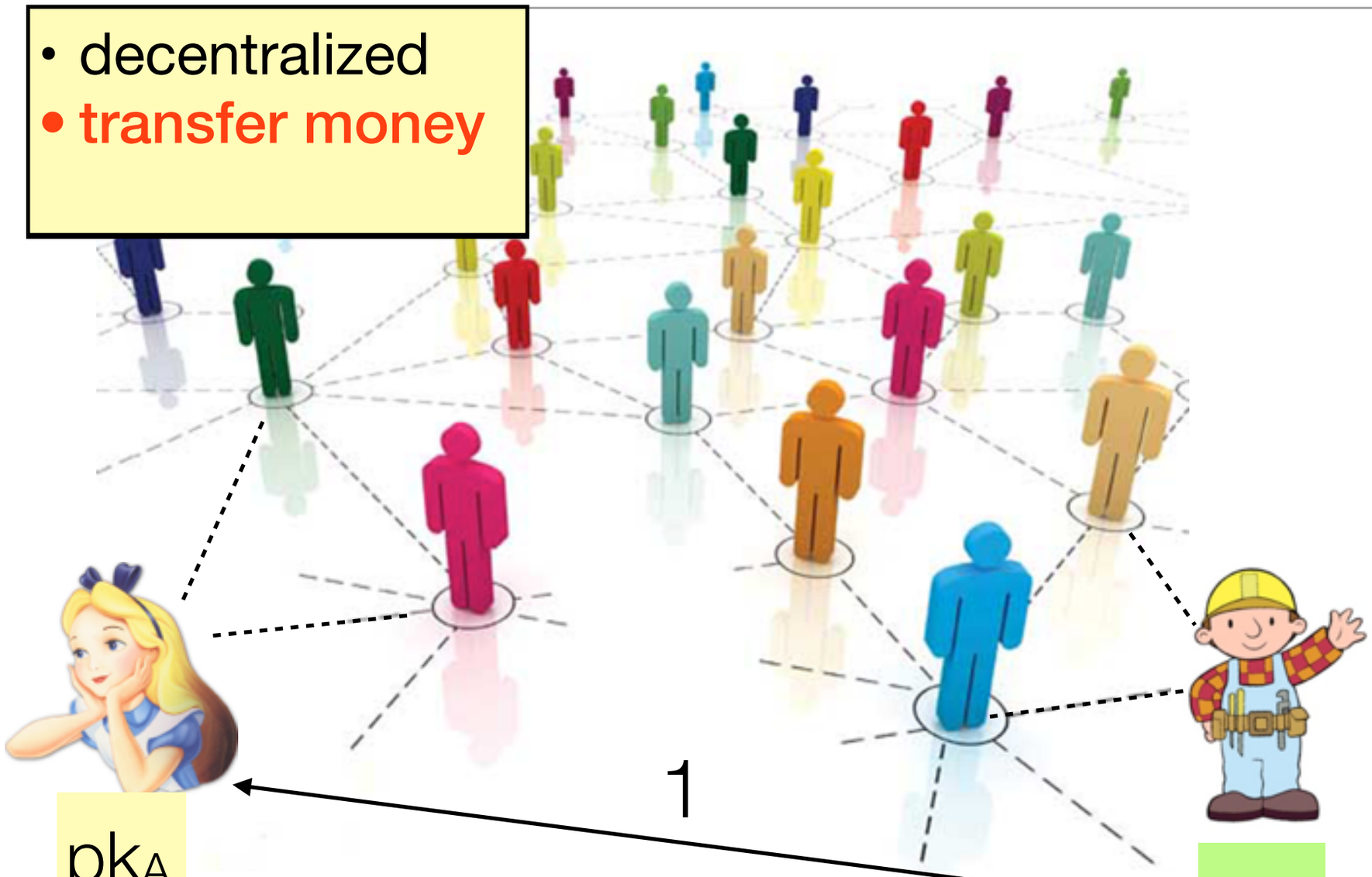

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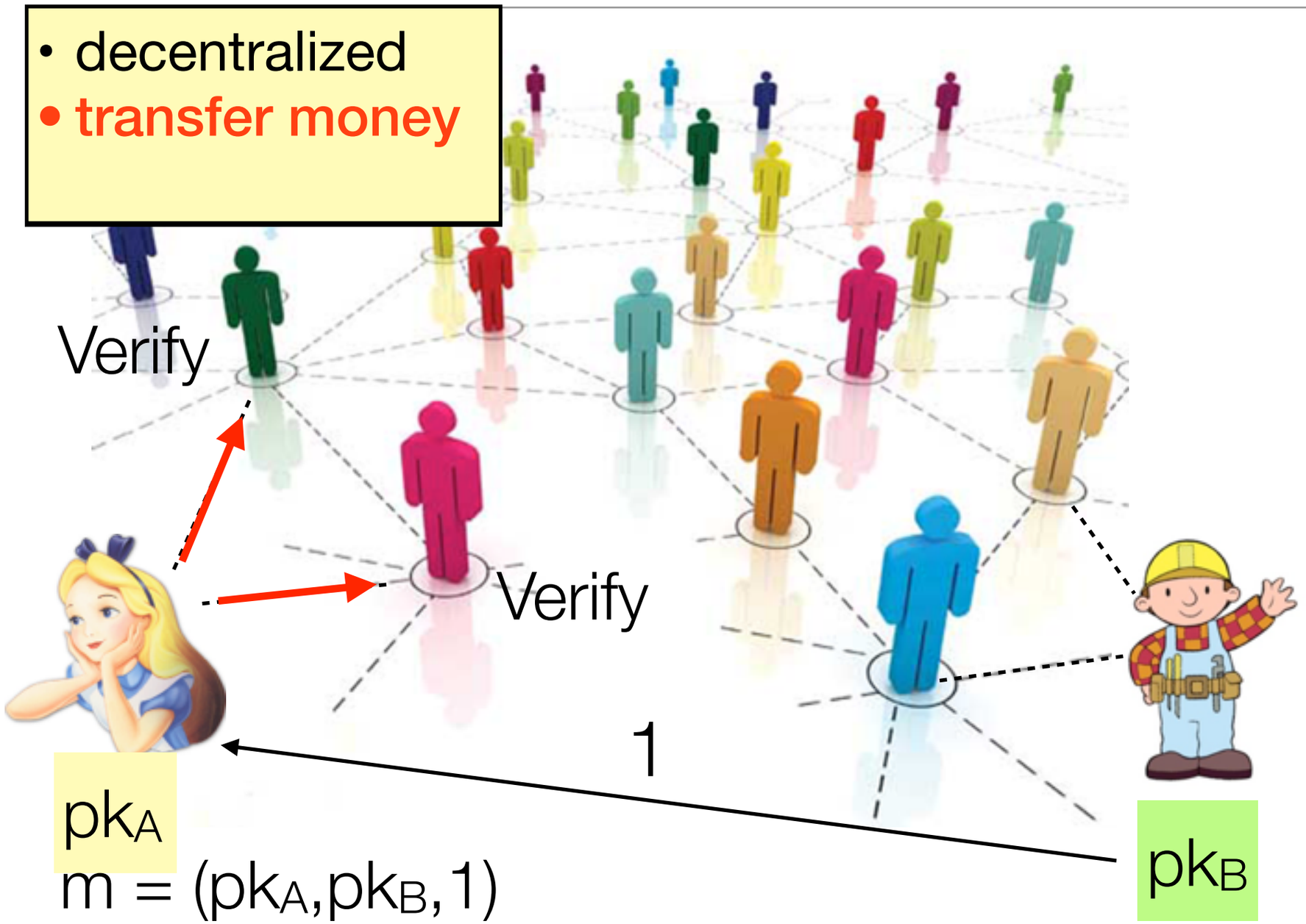

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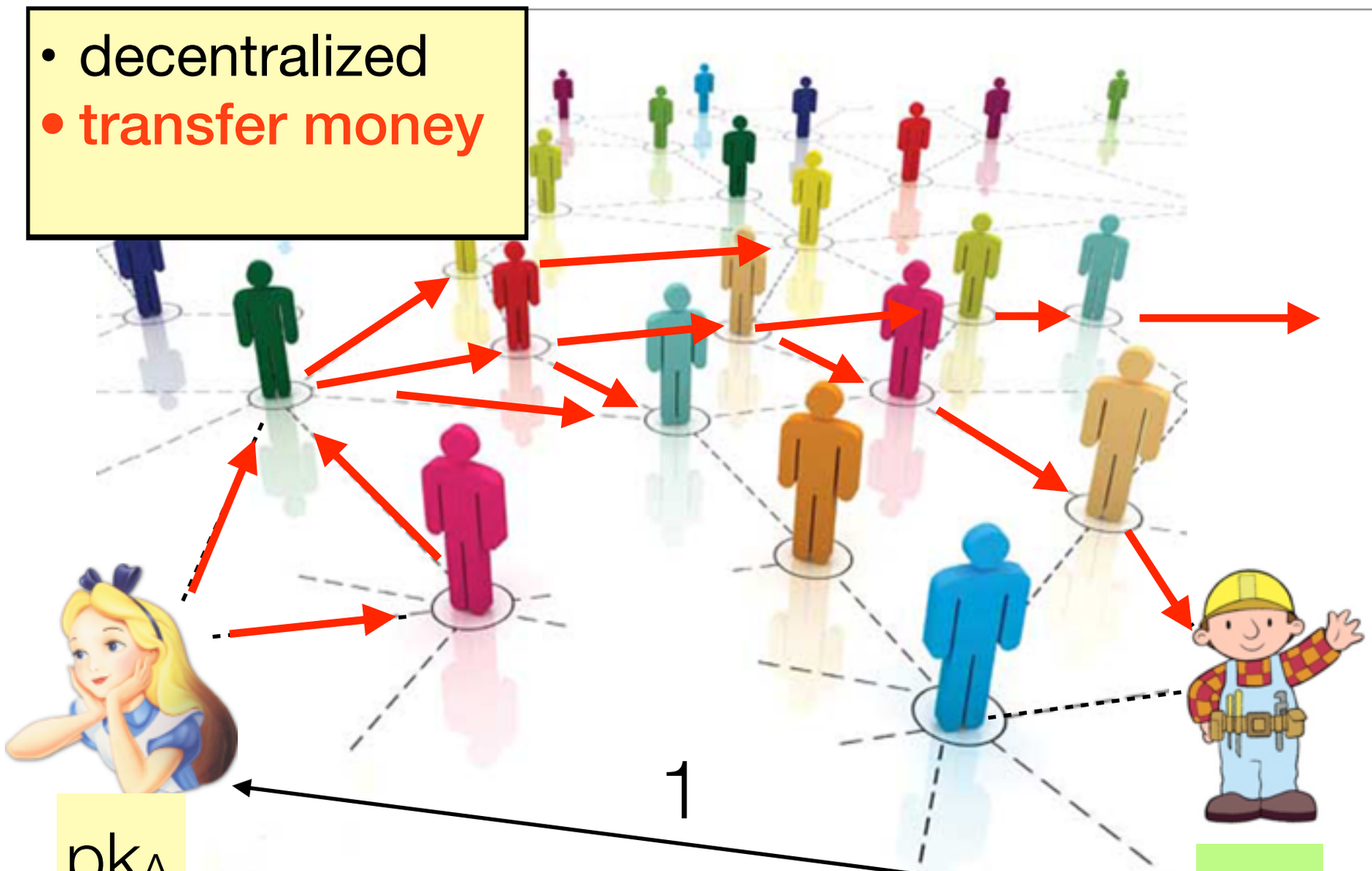

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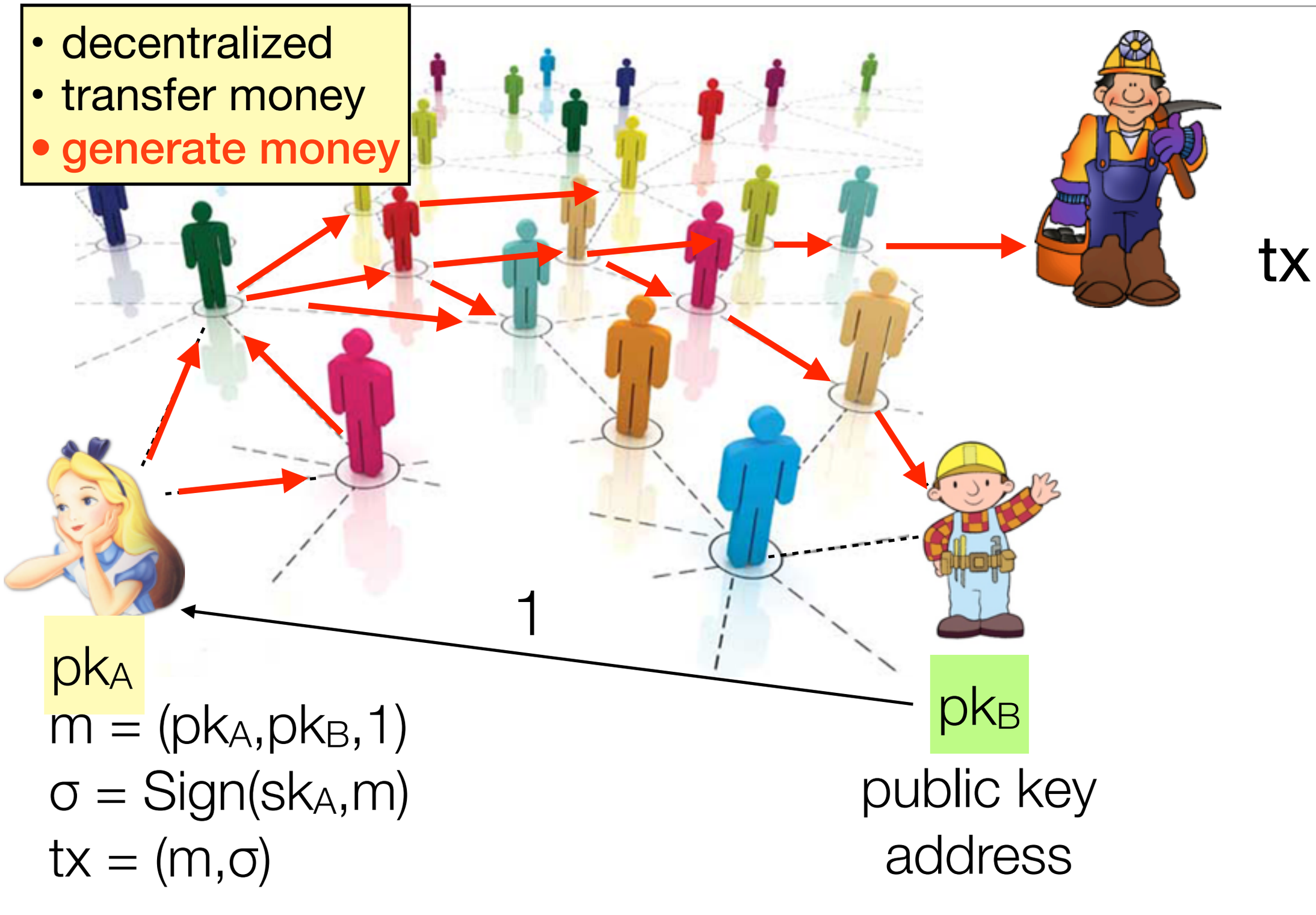

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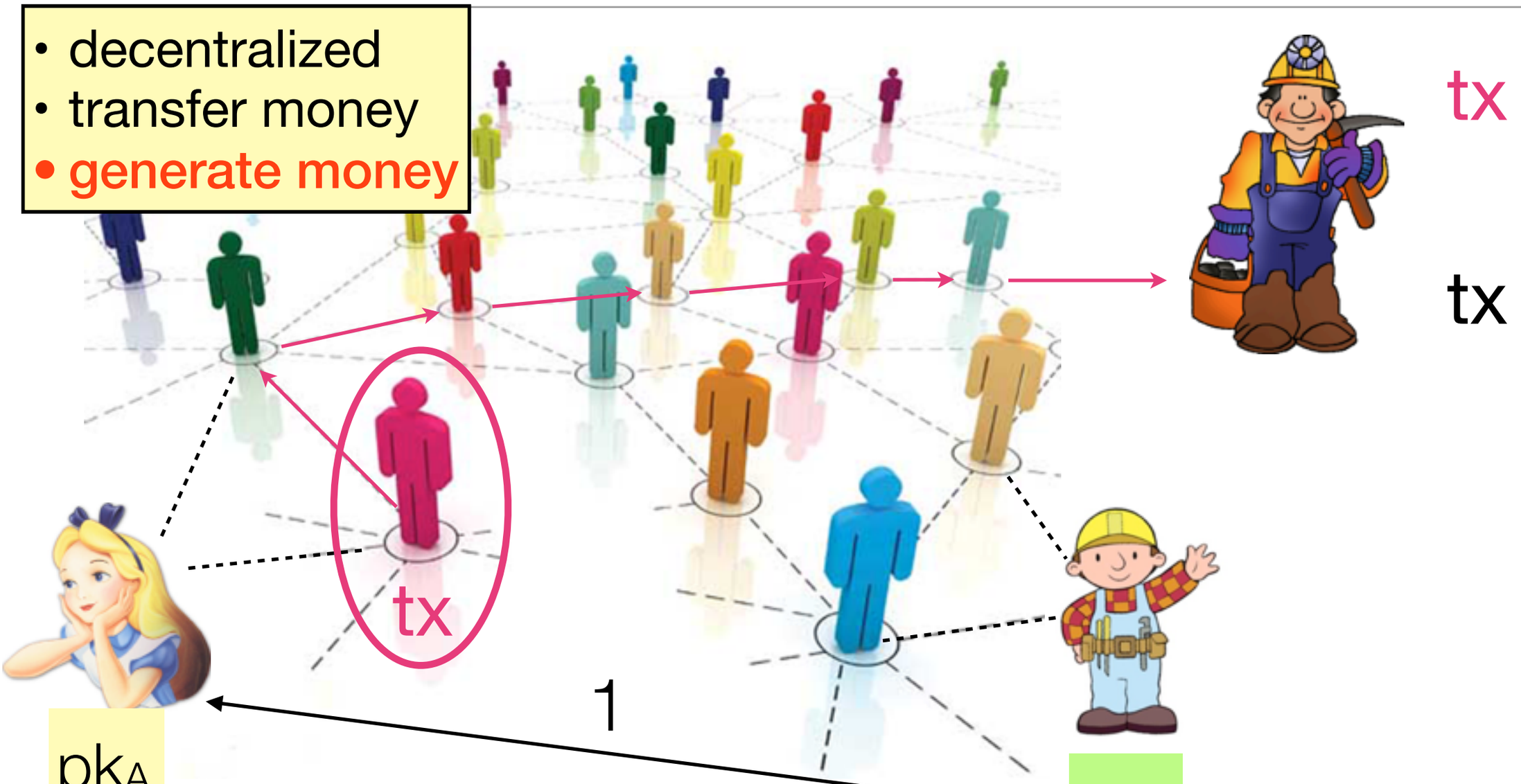

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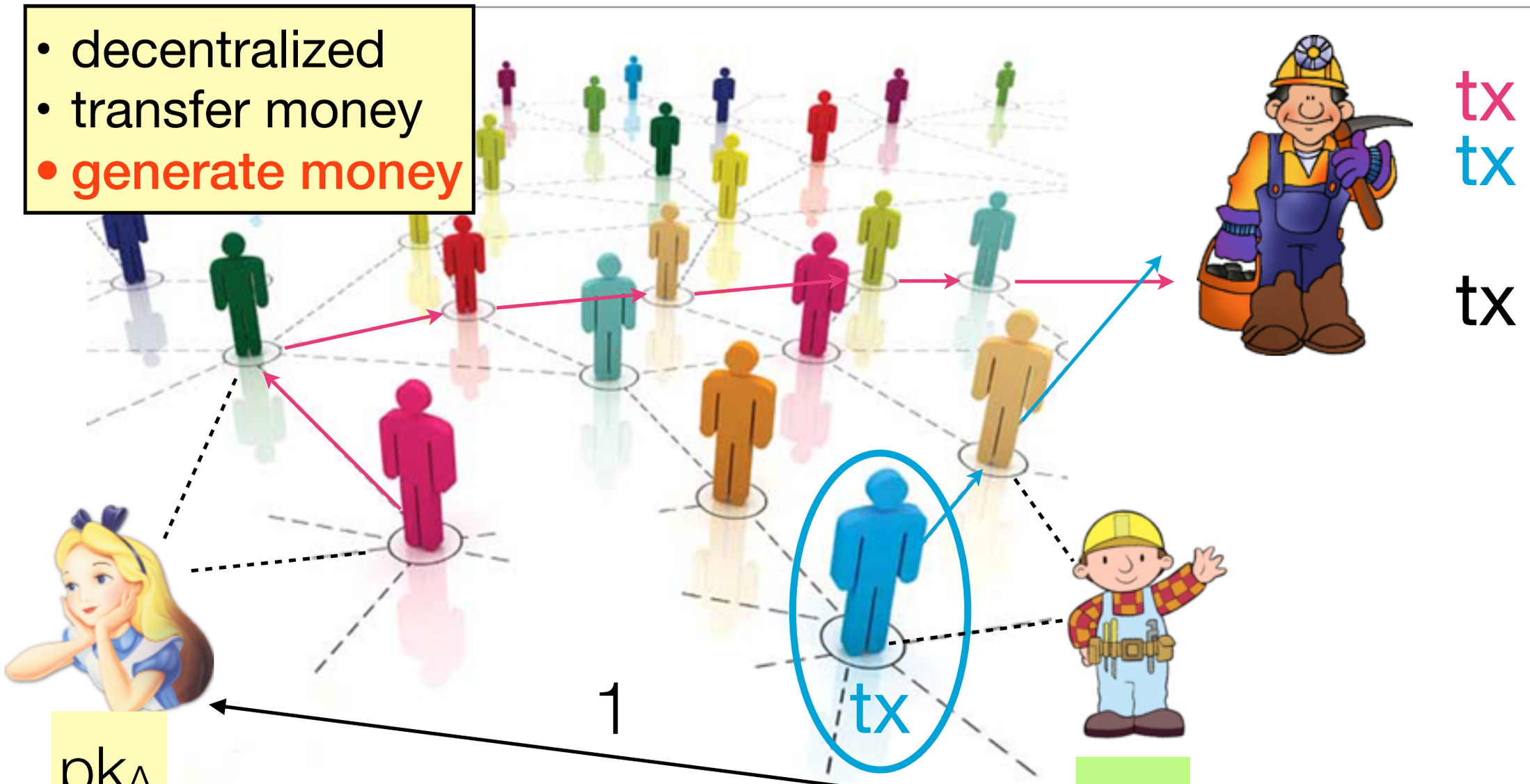

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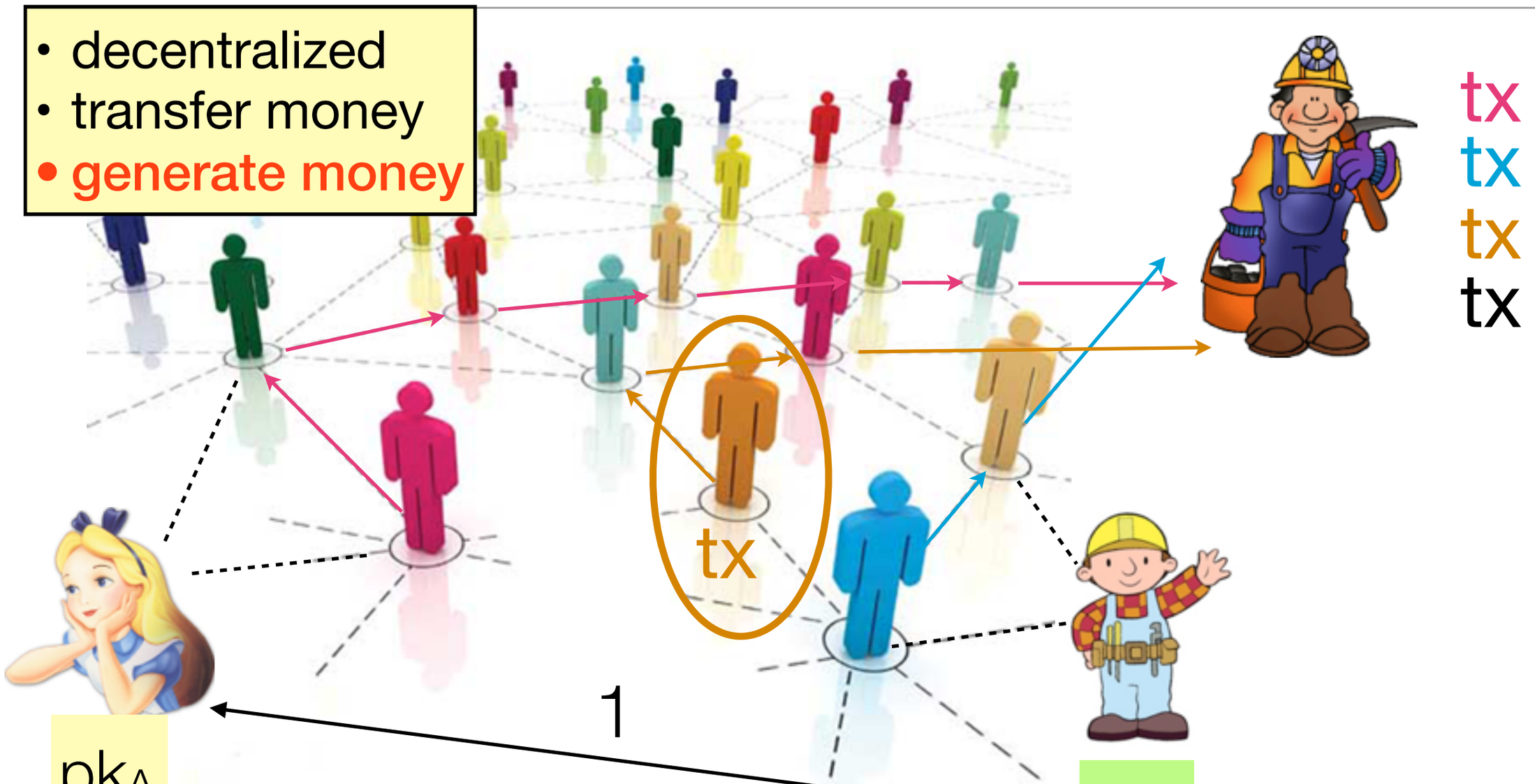

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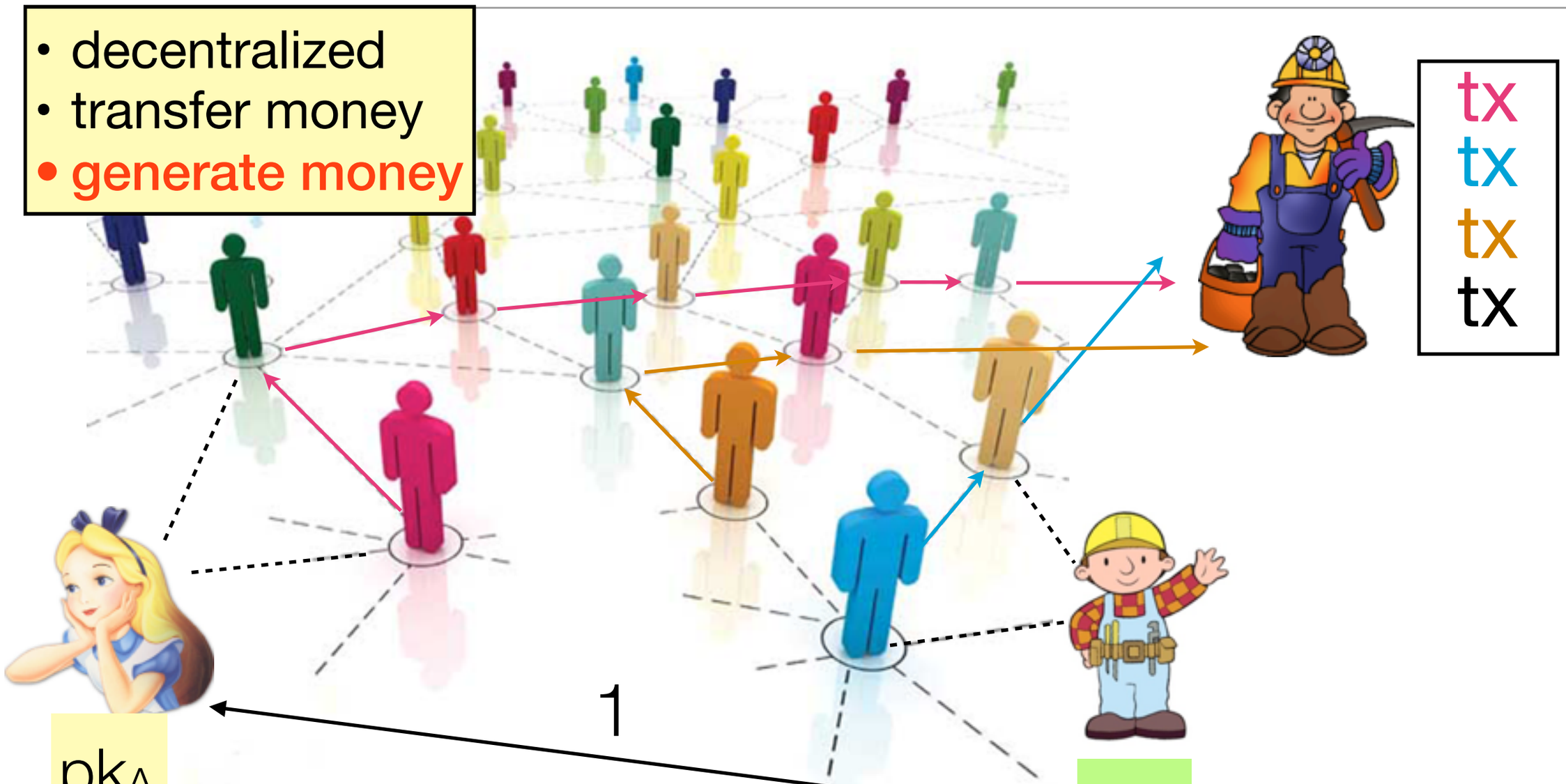

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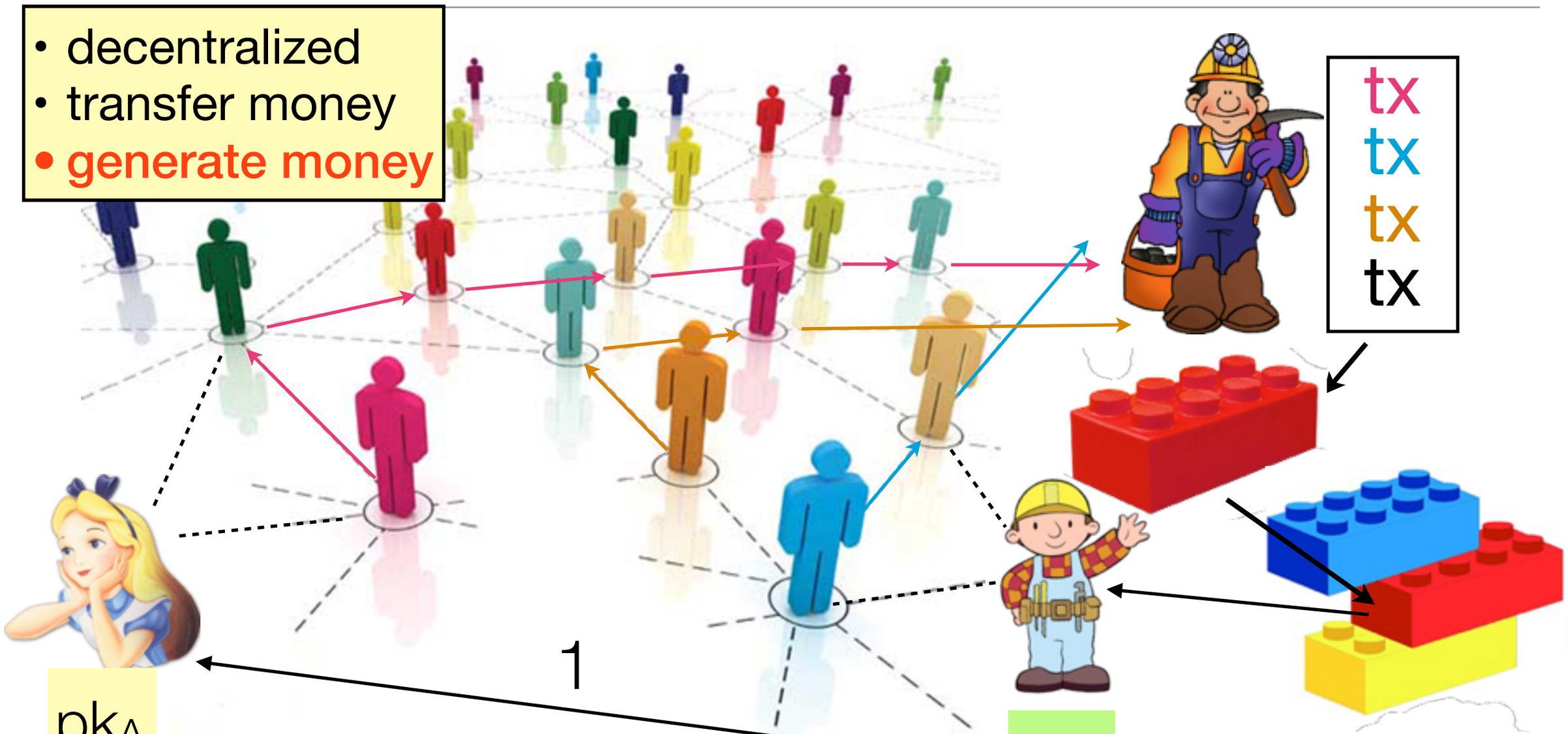

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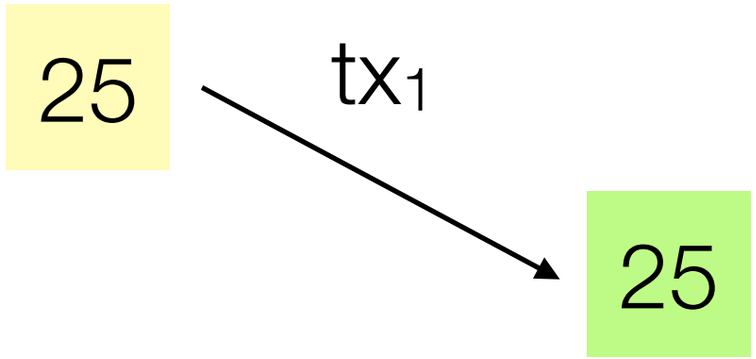

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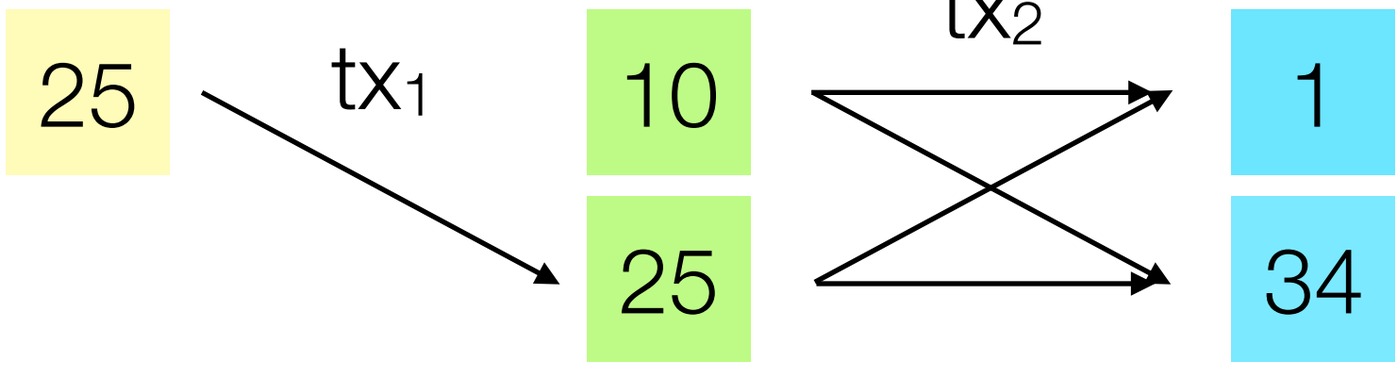

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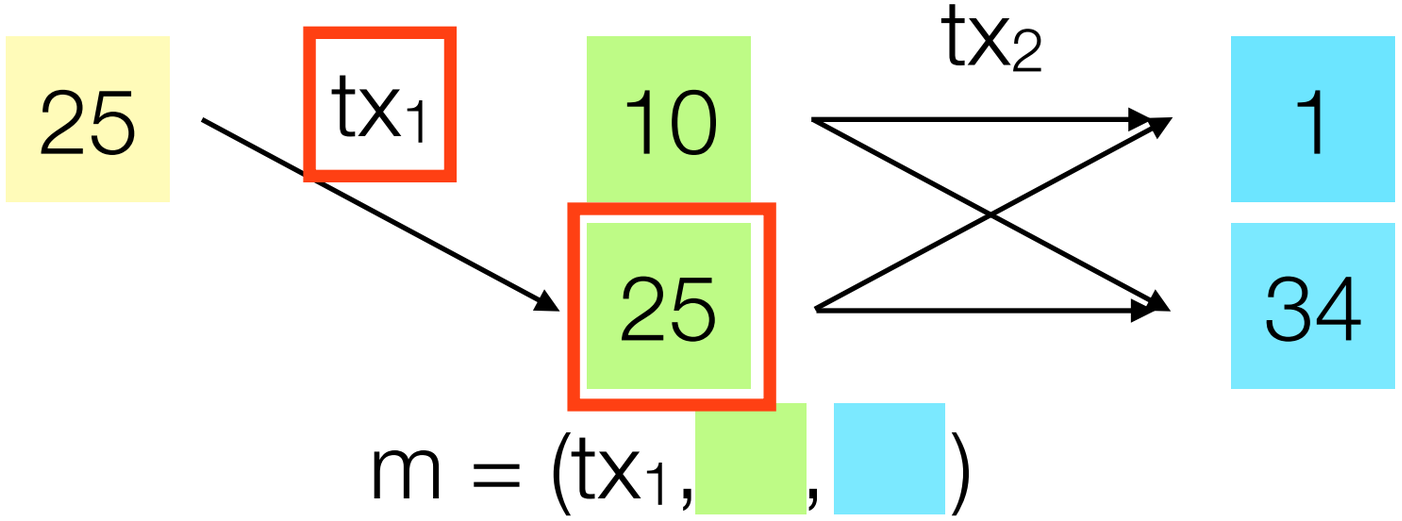

To spend bitcoins, a user must indicate the previous transaction

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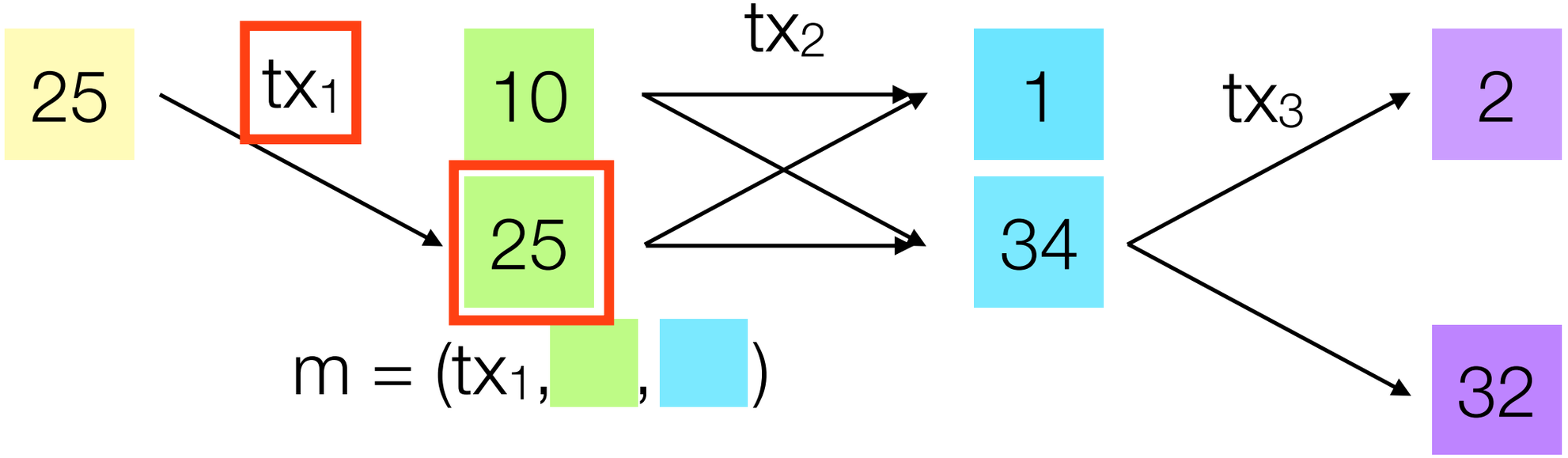

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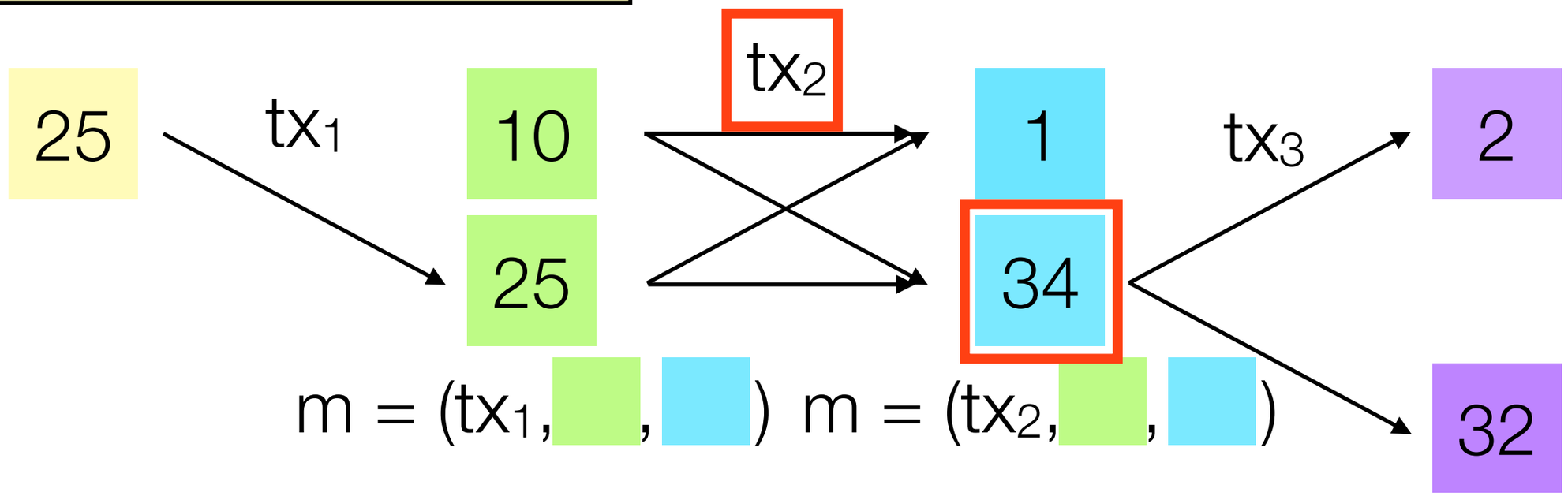

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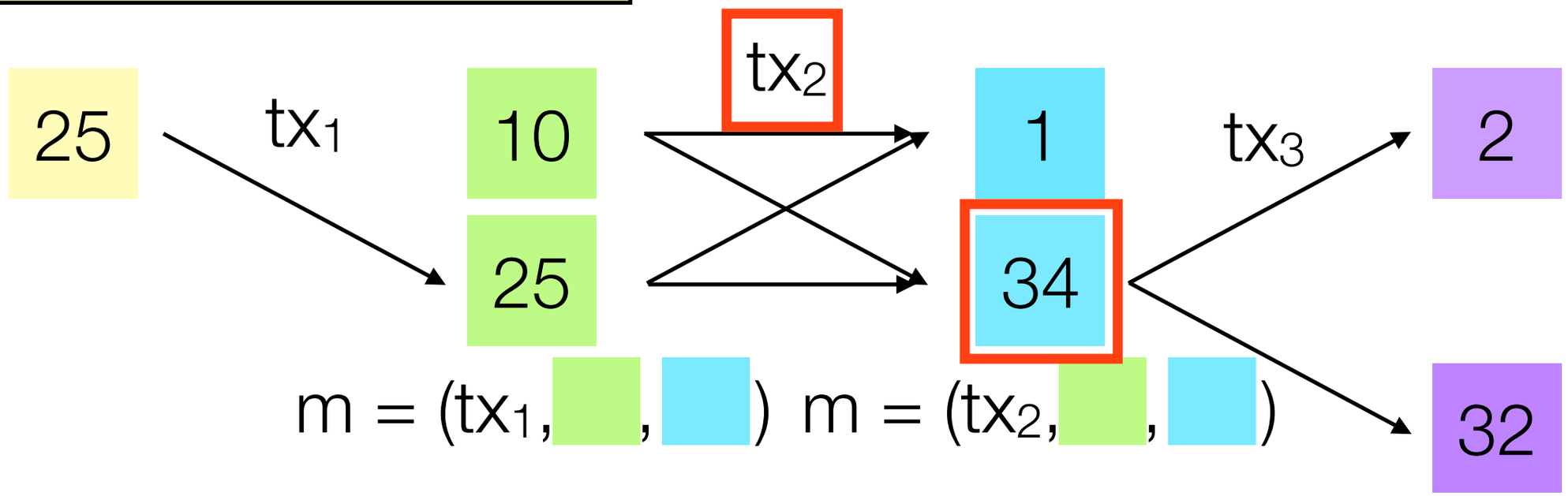

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All bitcoins received in a transaction must be spent all at once

How to identify users? [**M**PGLMVS IMC13]

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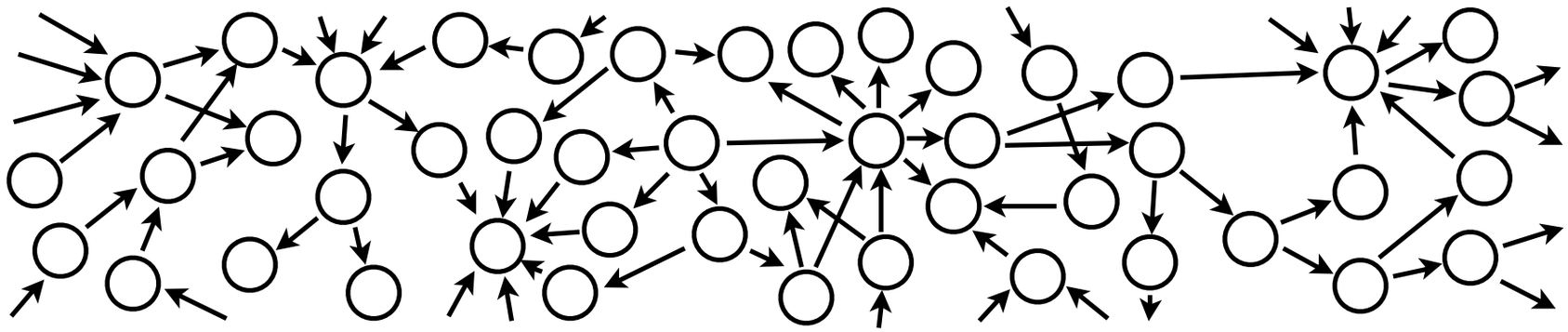

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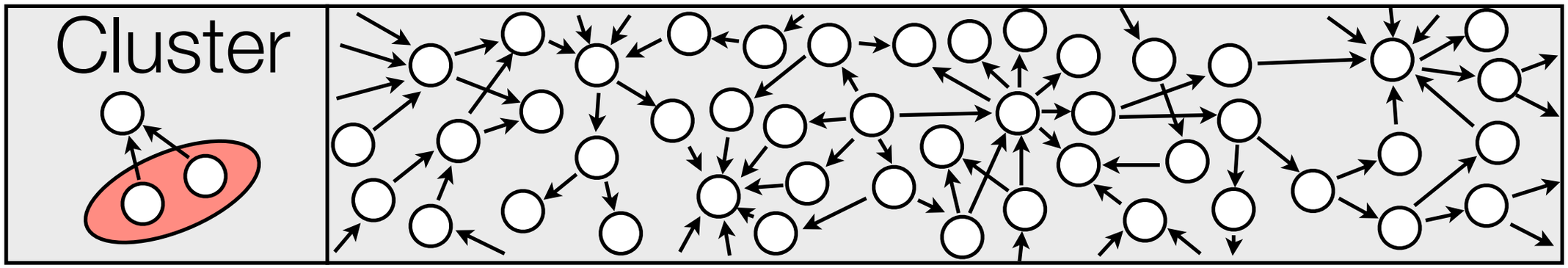

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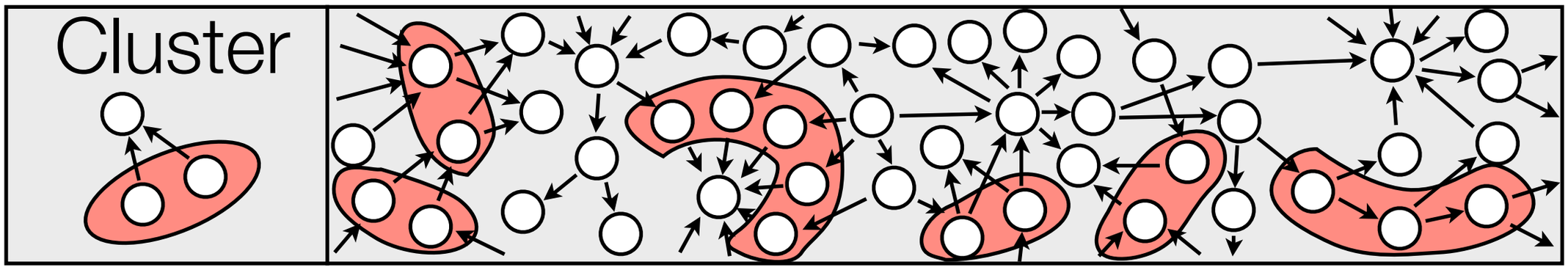

Collapse into a more manageable graph of clusters of public keys representing distinct entities

How to identify users? [**M**PGLMVS IMC13]

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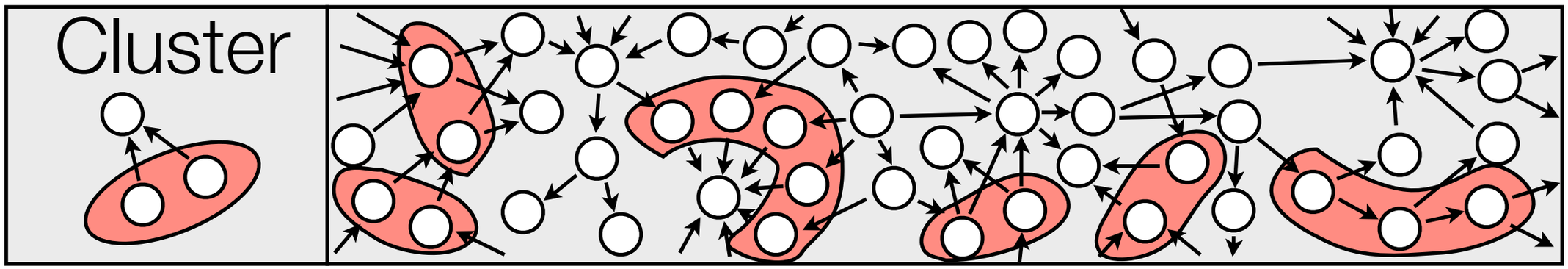
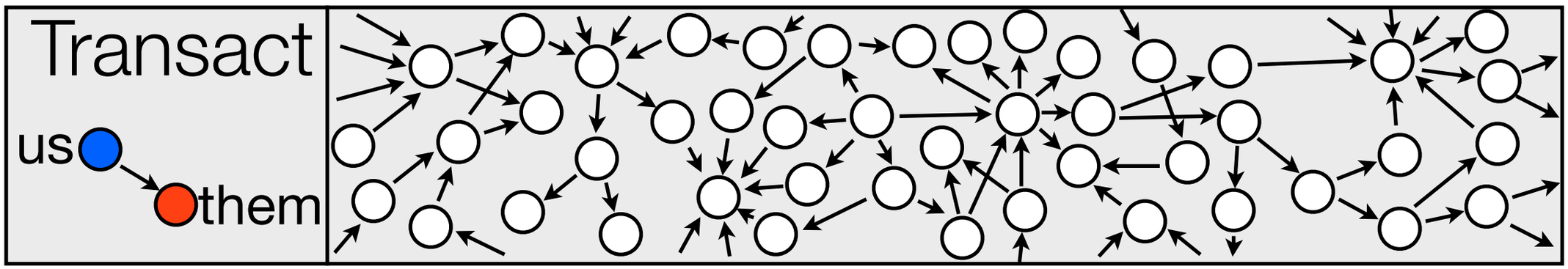


Collapse into a more manageable graph of clusters of public keys representing distinct entities



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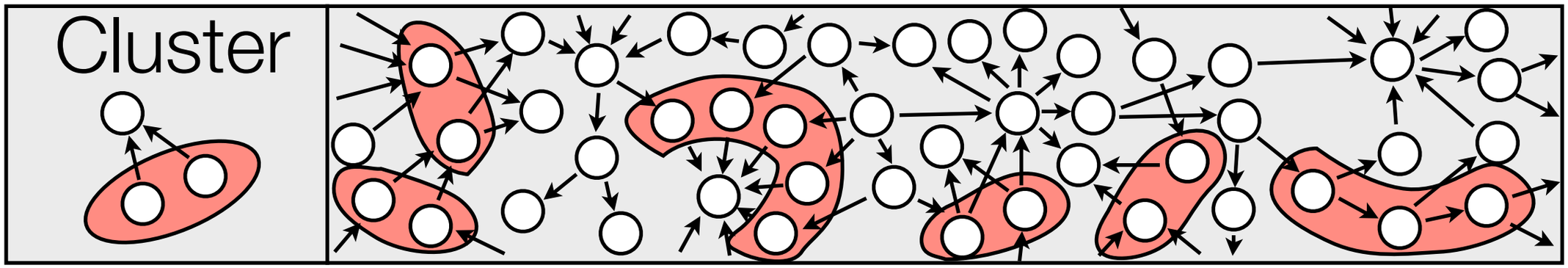

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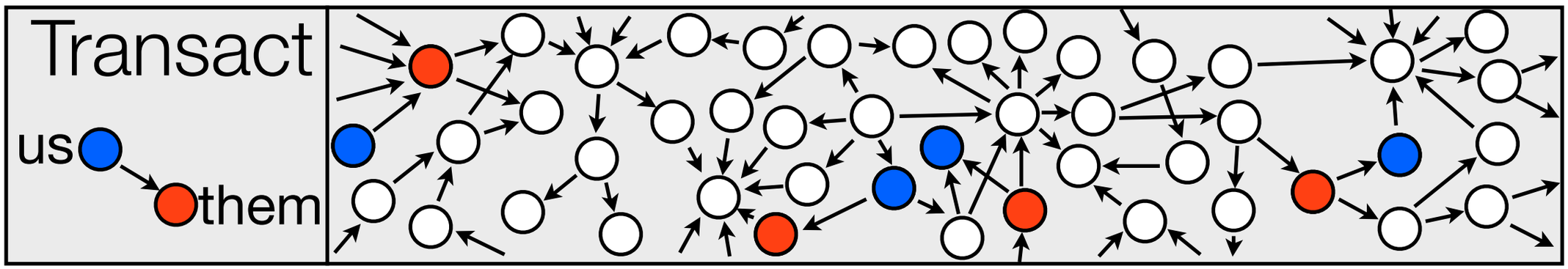
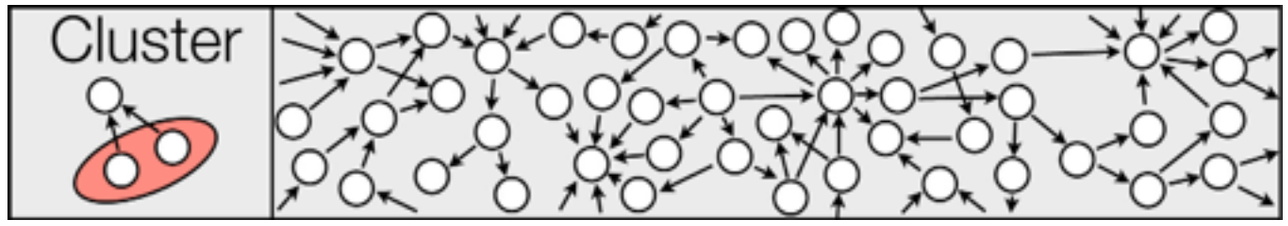
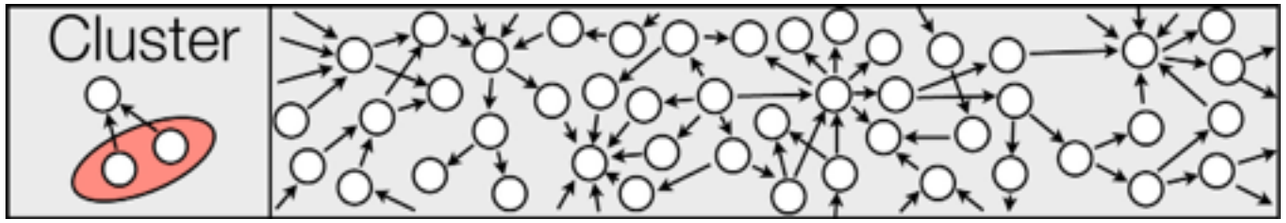


Collect ground truth data by participating in transactions

Clustering by inputs



Clustering by inputs



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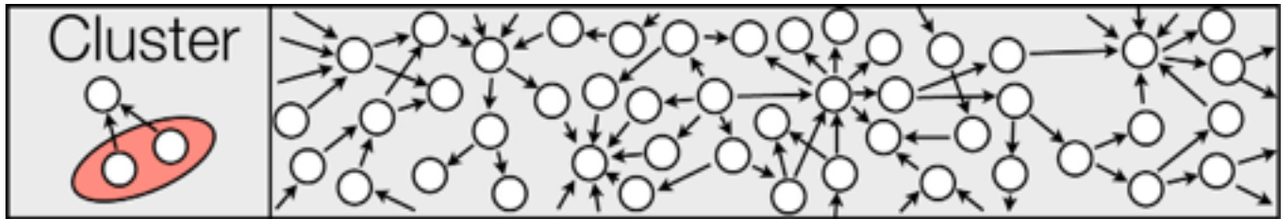
Clustering by inputs



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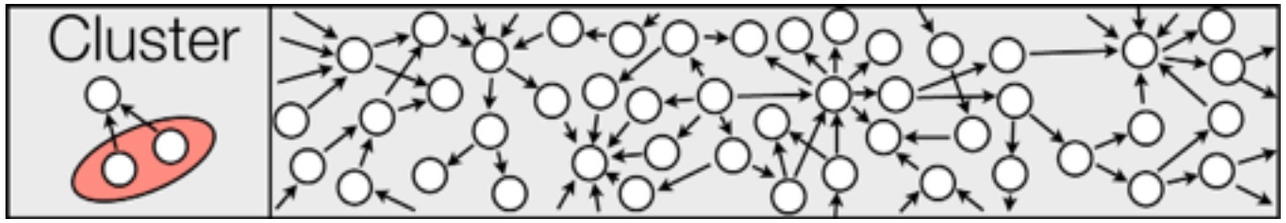

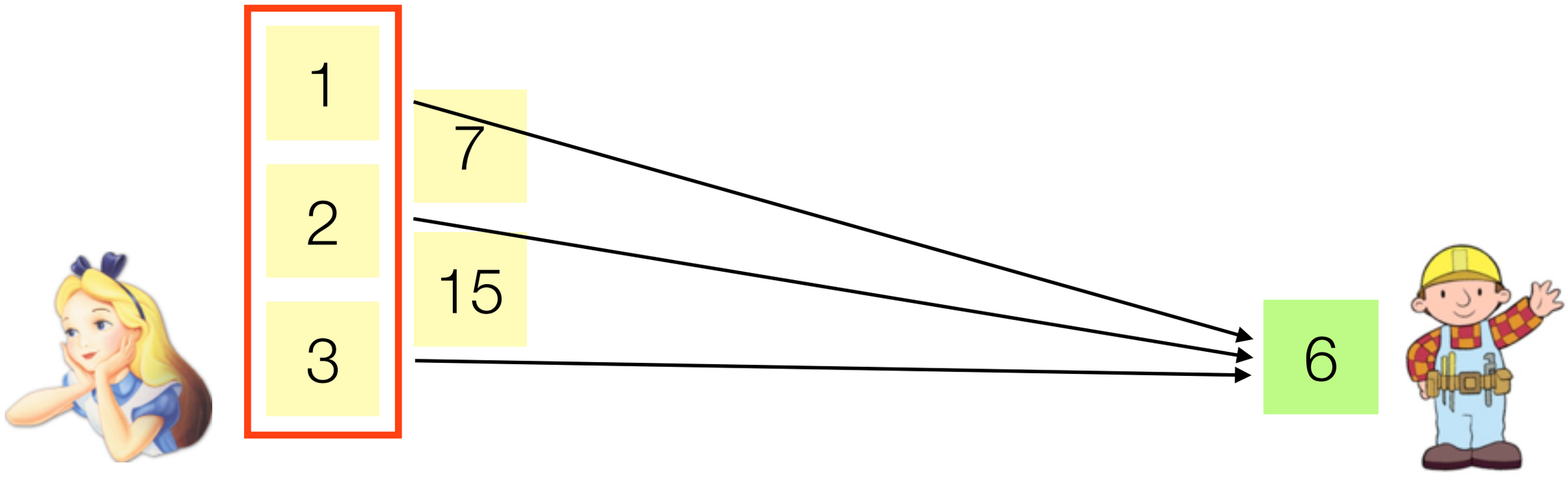

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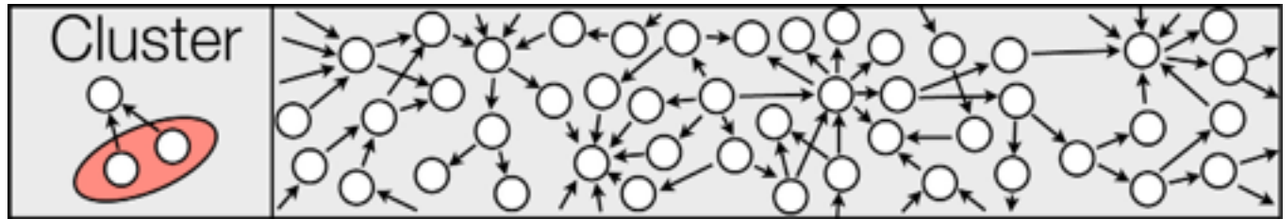
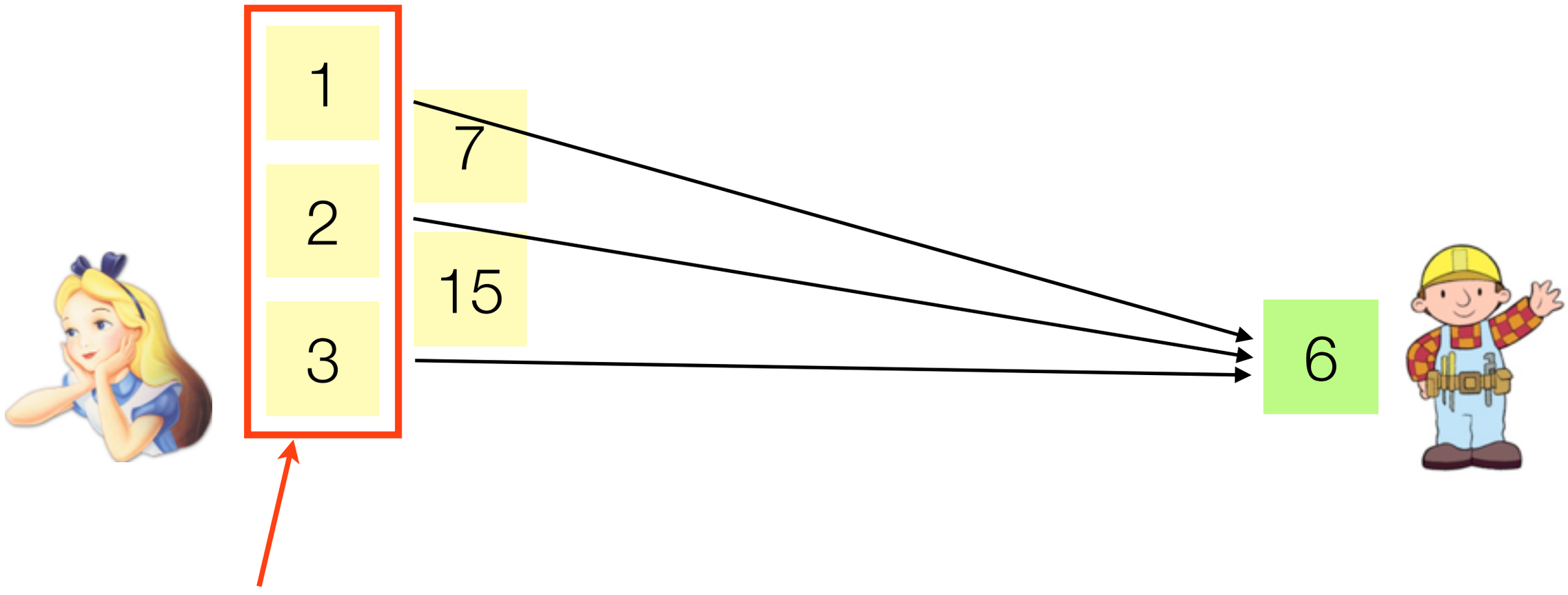
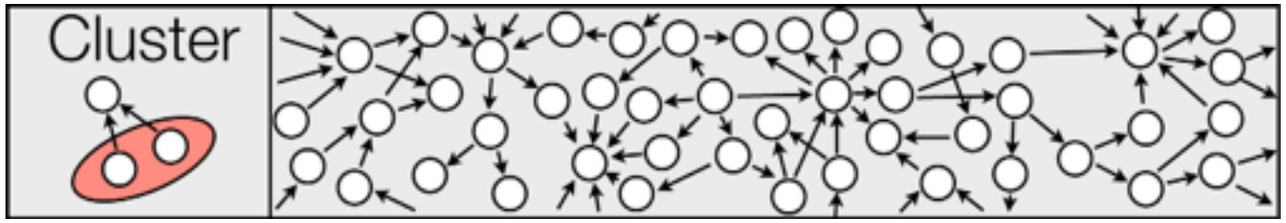




Heuristic #1: the same user controls these addresses [N08,RH11,RS13,A+13]

Change addresses



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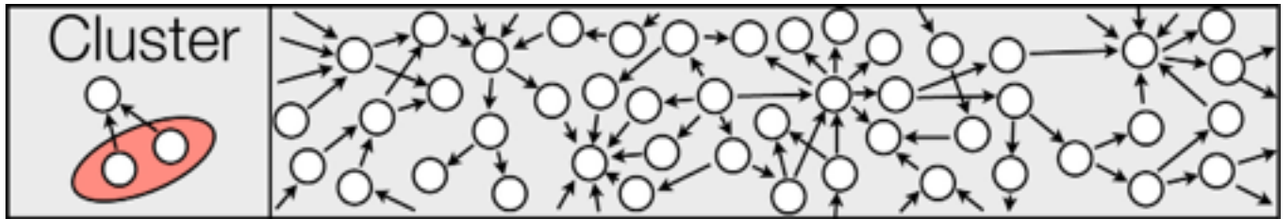
Change addresses



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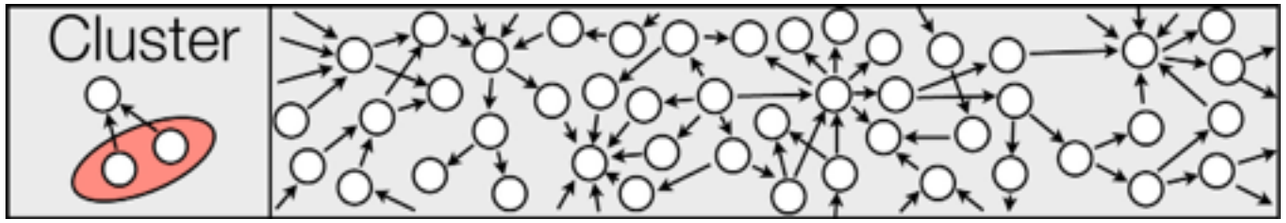
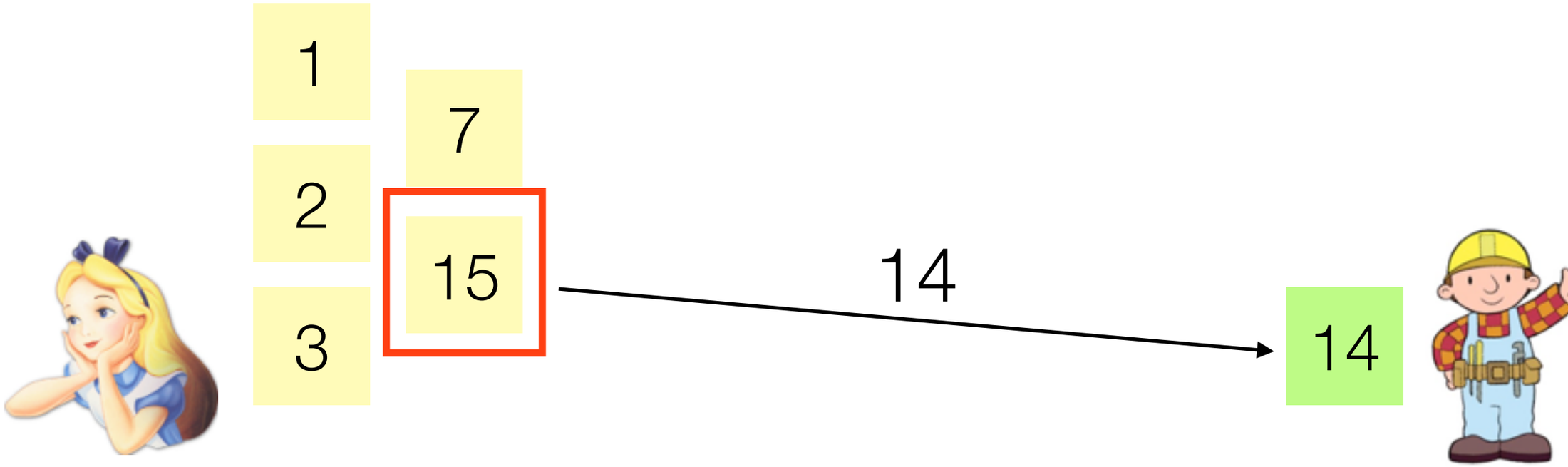
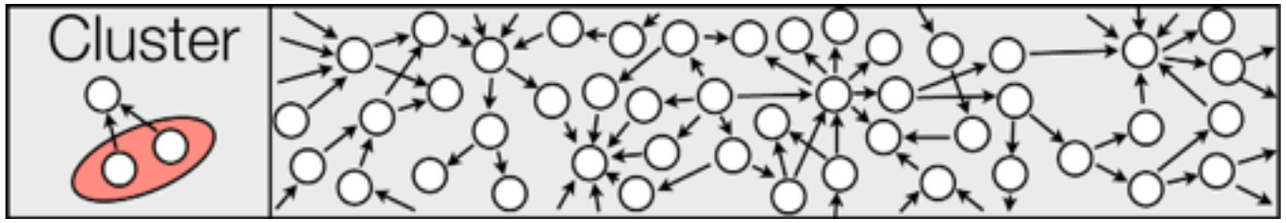
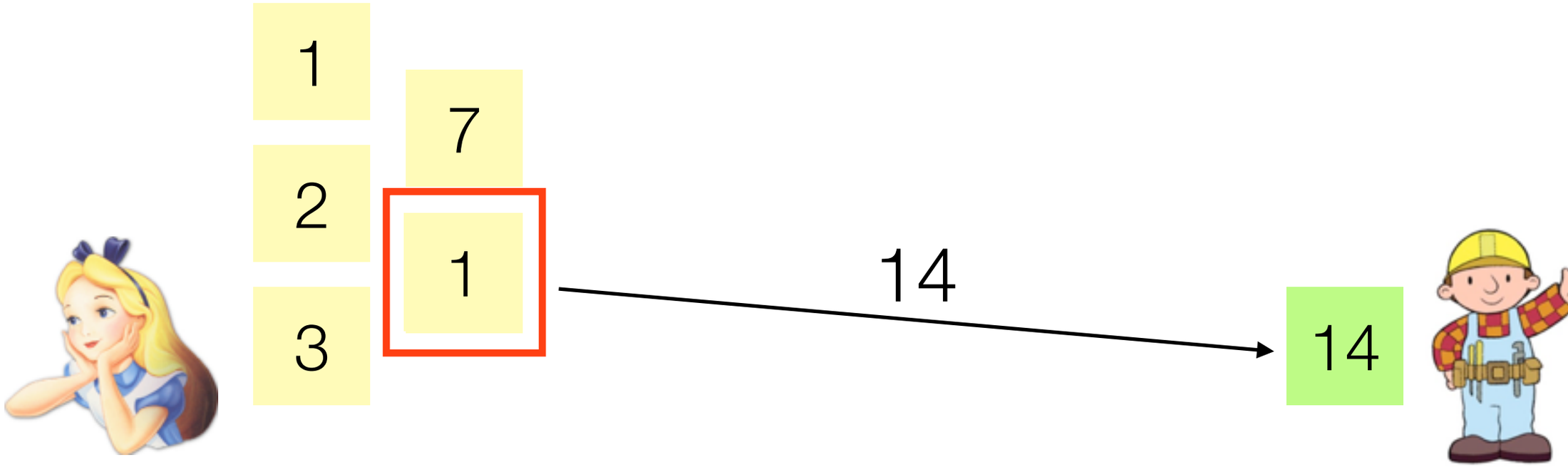
Change addresses



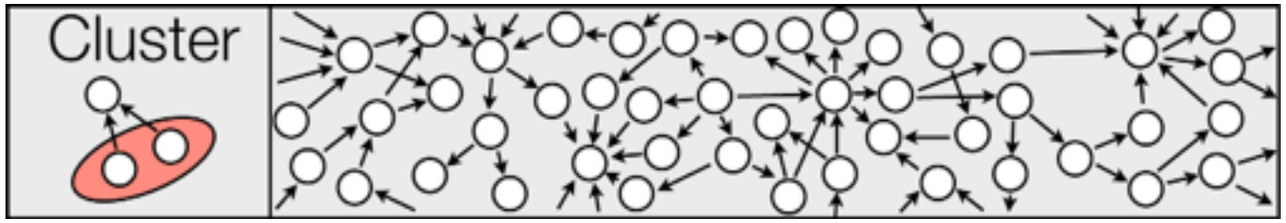


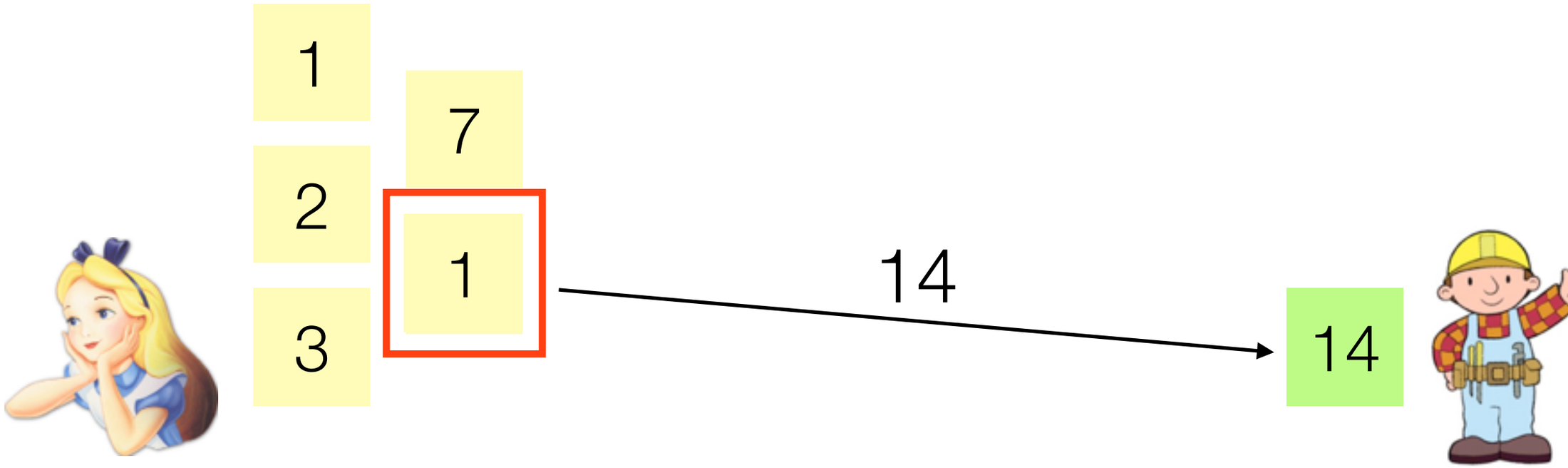
Change addresses





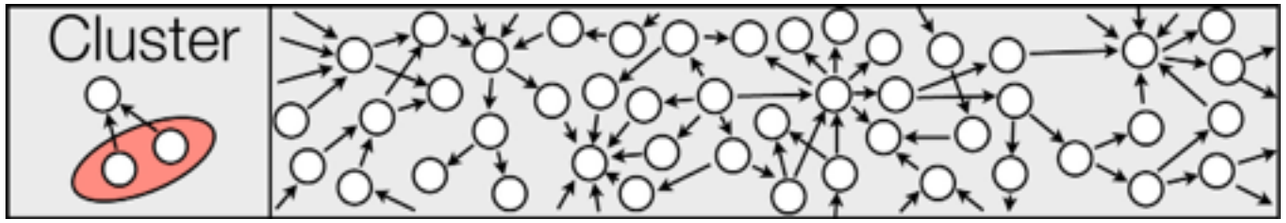
Change addresses





All bitcoins received in a transaction must be spent all at once

Change addresses



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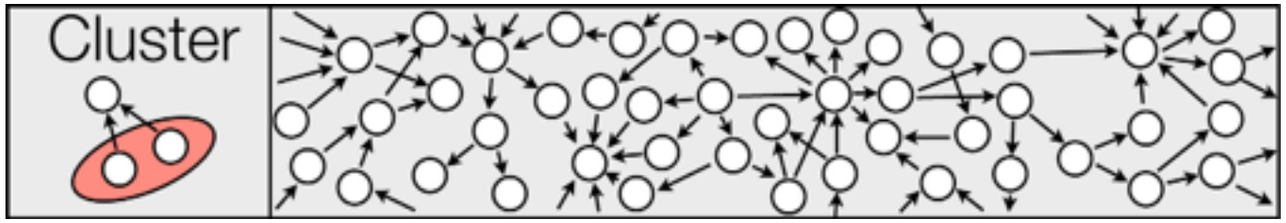

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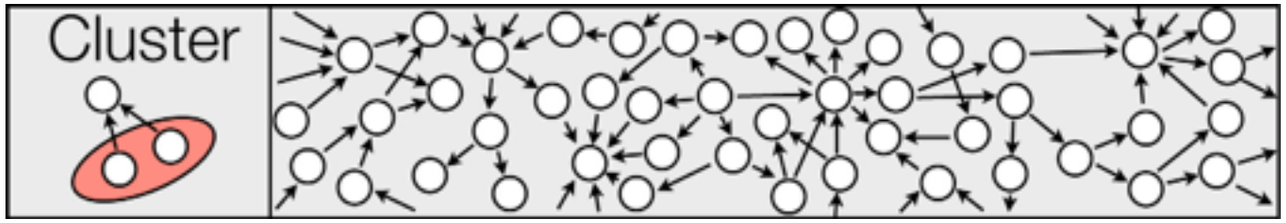

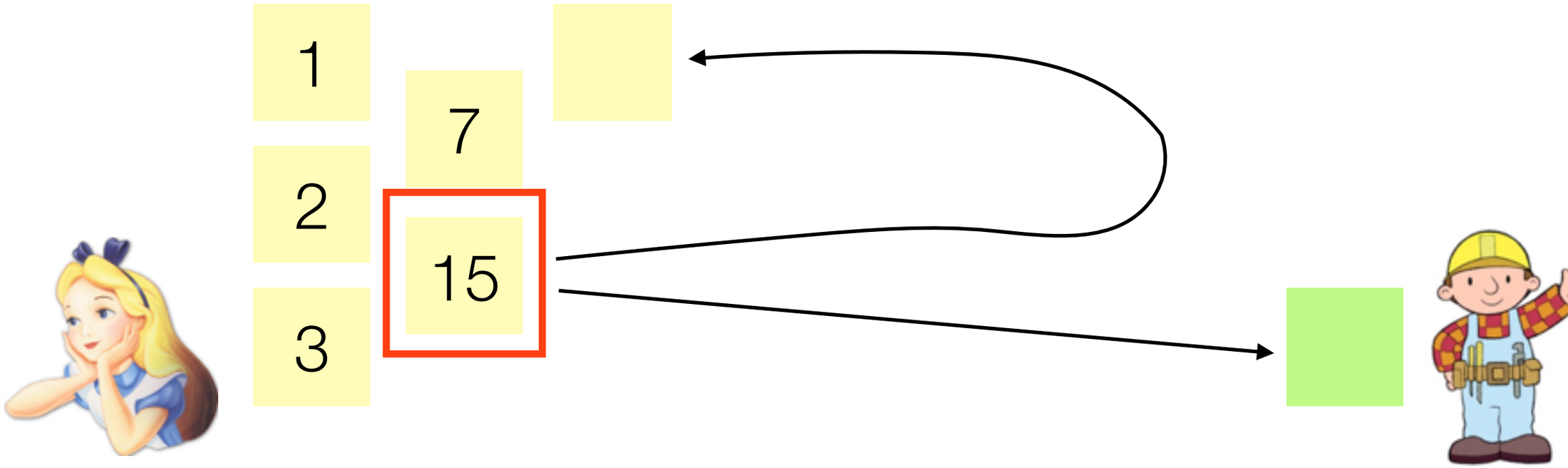

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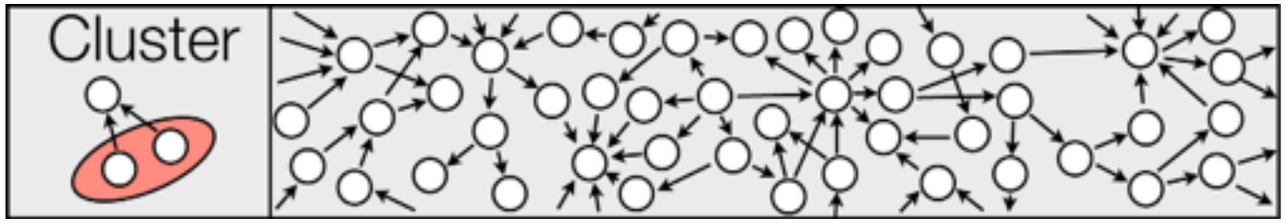
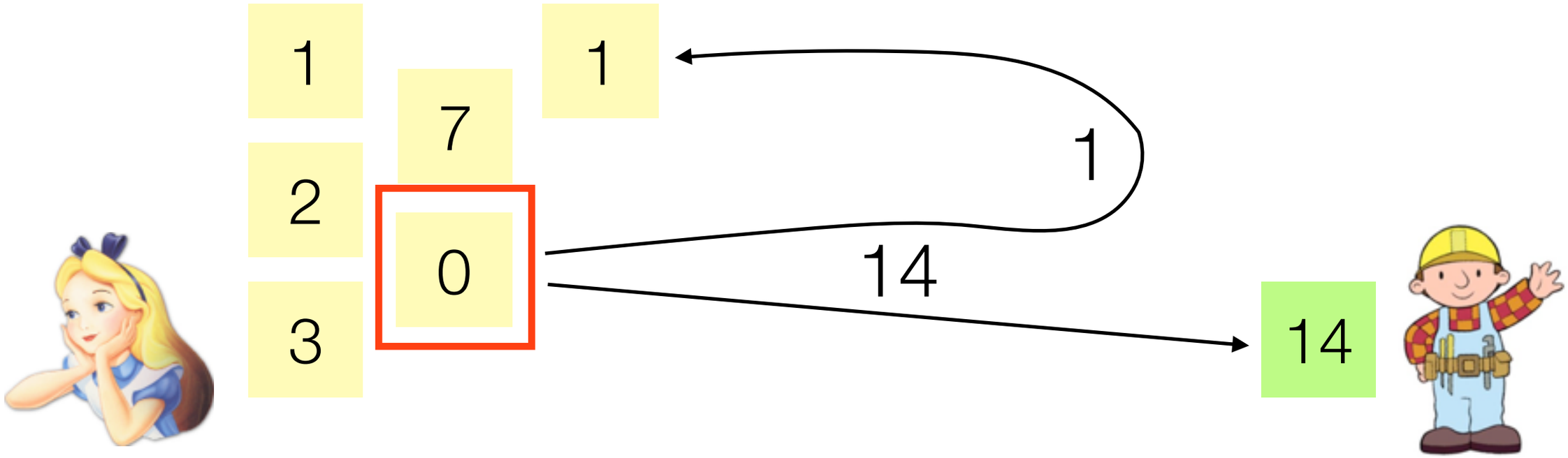
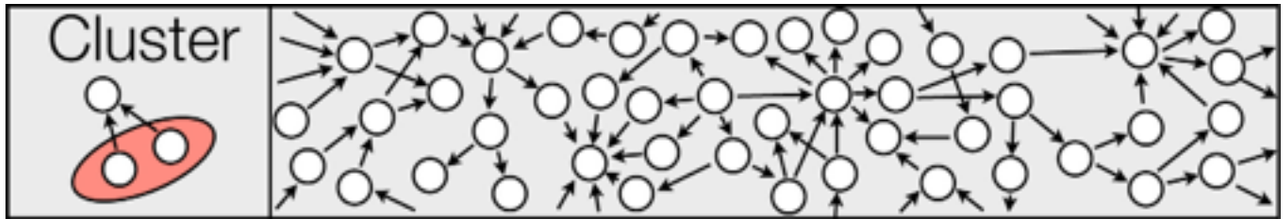
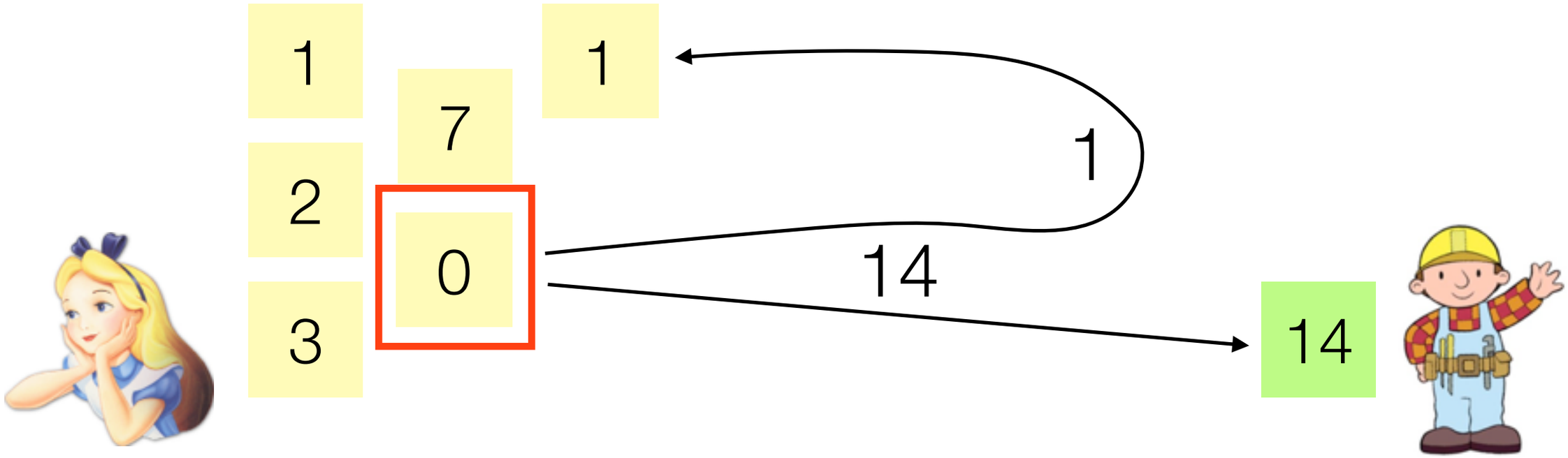




All bitcoins received in a transaction must be spent all at once

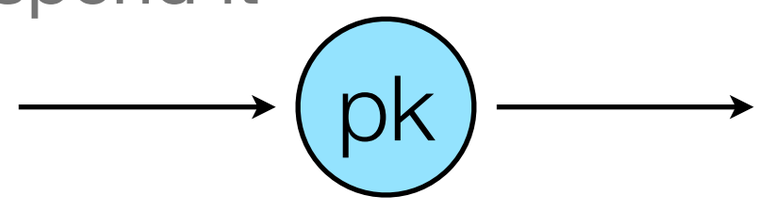
Change addresses



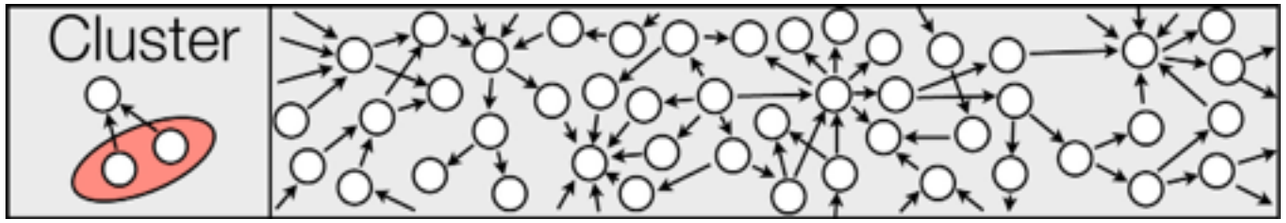


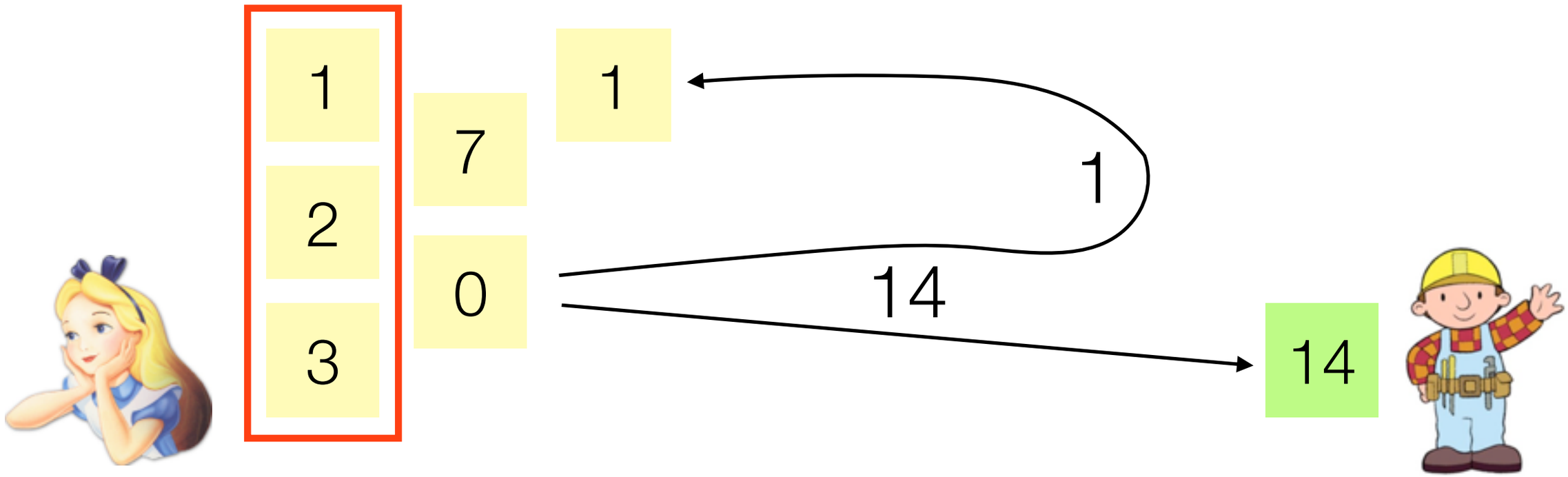
All bitcoins received in a transaction must be spent all at once

In the standard idiom, change addresses are used at most twice: to receive change and to spend it

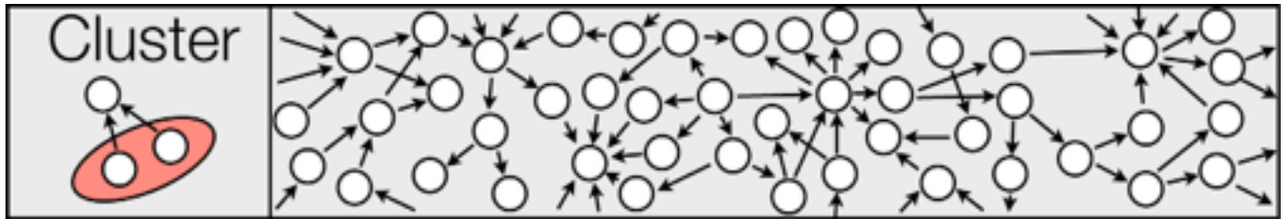


Clustering by change





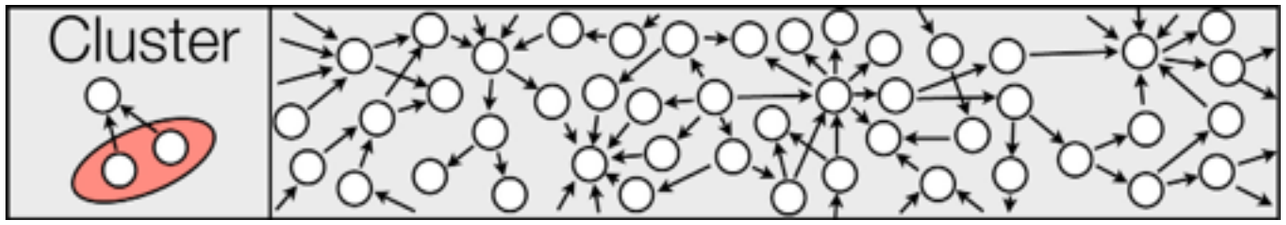
Clustering by change



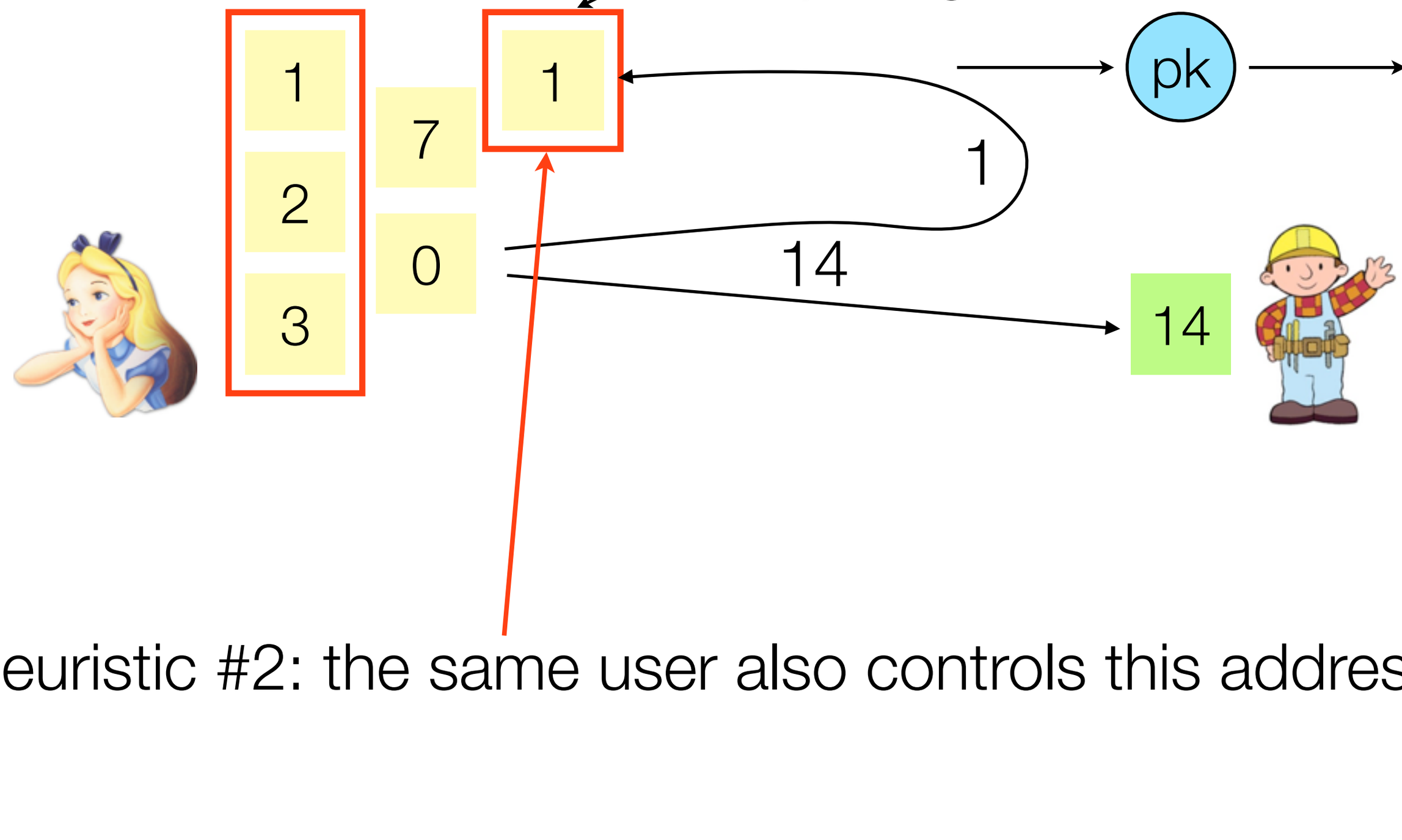
identify using one-time behavior

1
2
3
7
0
1
1
pk
14
14

Clustering by change

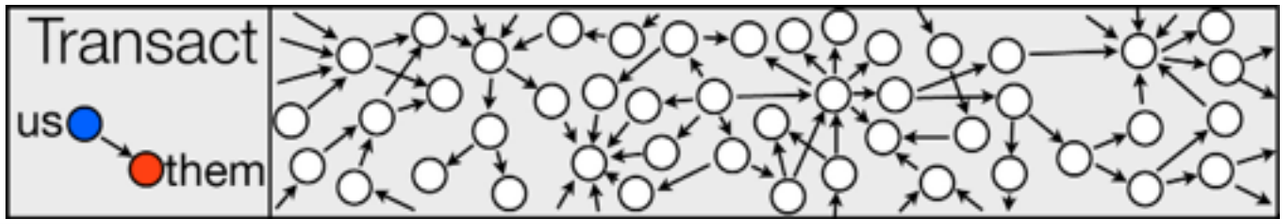


identify using one-time behavior

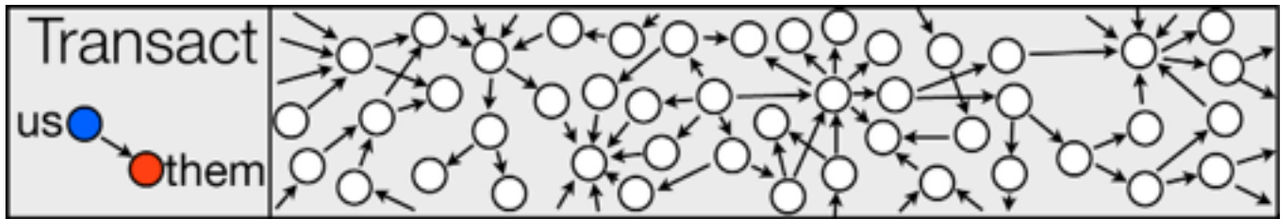


Heuristic #2: the same user also controls this address

Data collection

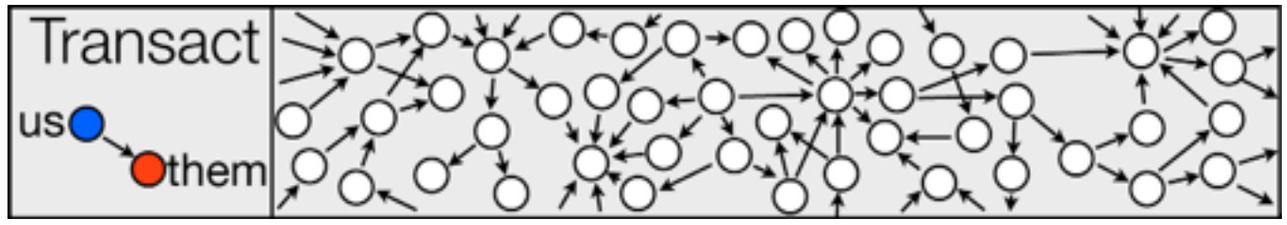


Data collection



Engaged in transactions with:

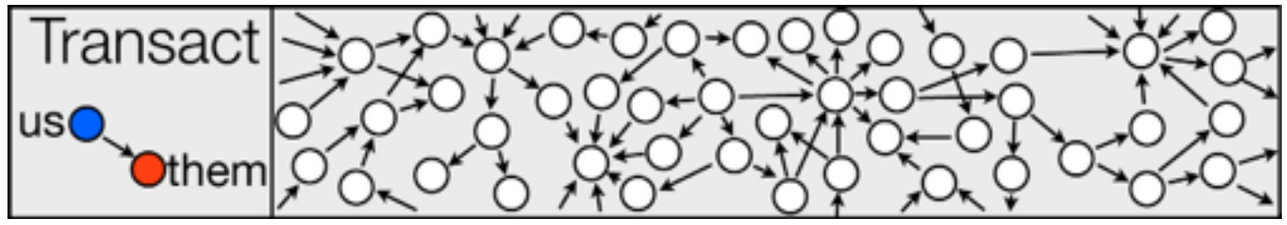
Data collection



Engaged in transactions with:

- Exchanges

Data collection

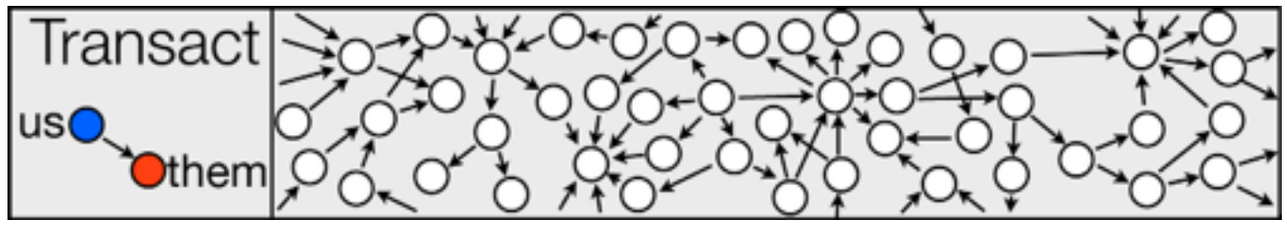


Engaged in transactions with:

- Exchanges

- Vendors

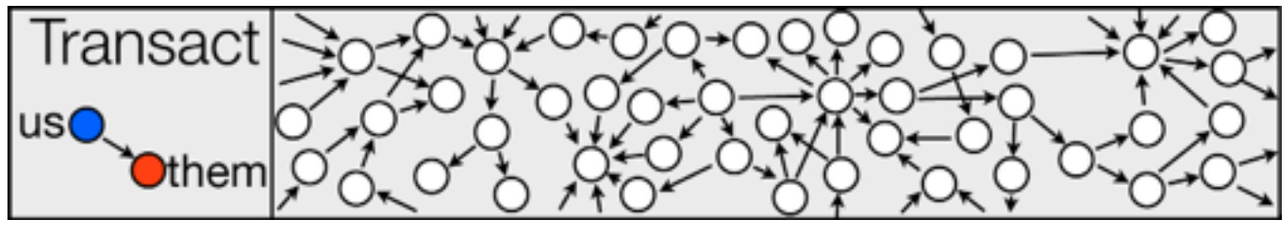
Data collection



Engaged in transactions with:

- Exchanges
- Vendors
- Mining pools

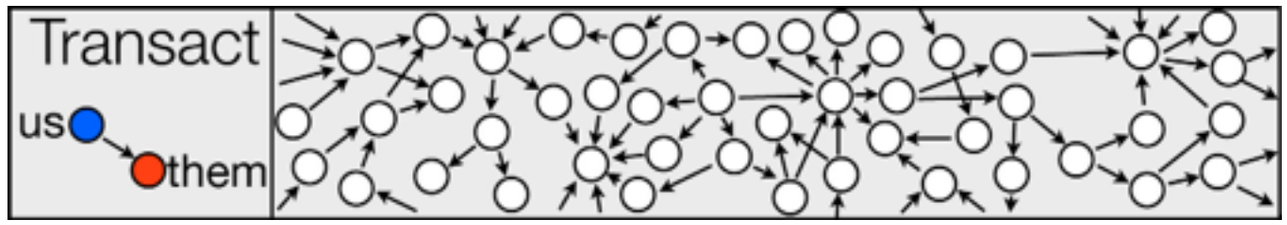
Data collection



Engaged in transactions with:

- Exchanges
- Vendors
- Mining pools
- Gambling sites

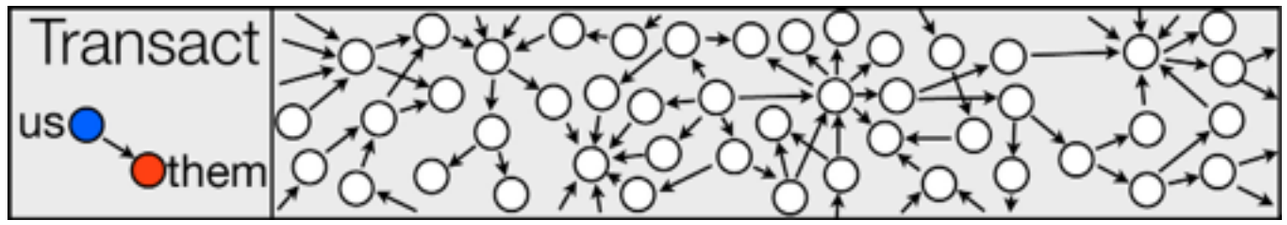
Data collection



Engaged in transactions with:

- Exchanges
- Vendors
- Mining pools
- Gambling sites
- Wallet services

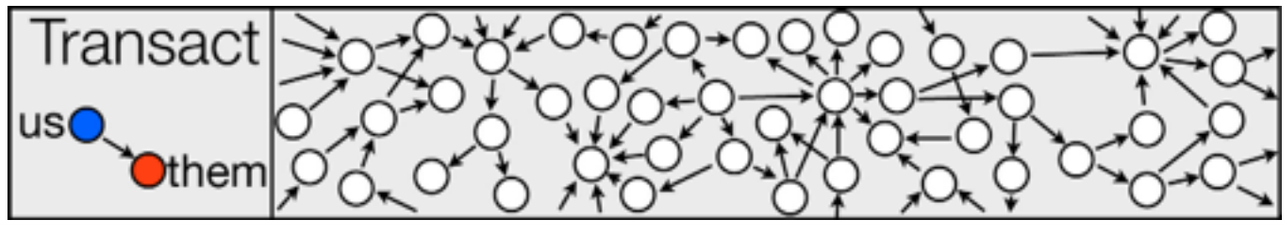
Data collection



Engaged in transactions with:

- Exchanges
- Vendors
- Mining pools
- Gambling sites
- Wallet services
- Mix services

Data collection

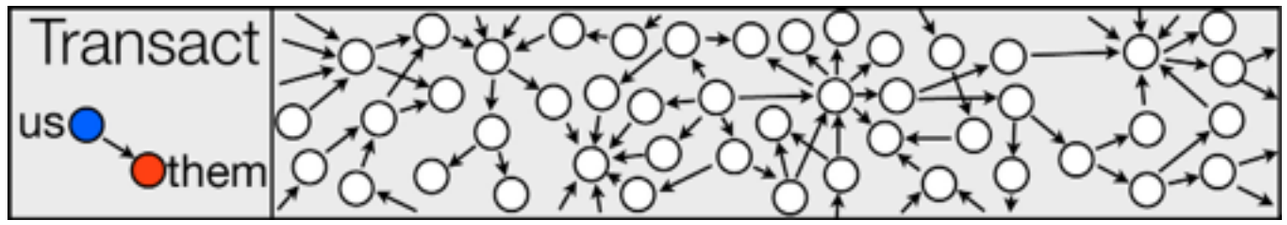


Engaged in transactions with:

- Exchanges
- Vendors
- Mining pools
- Gambling sites
- Wallet services
- Mix services

Scraped published tags

Data collection



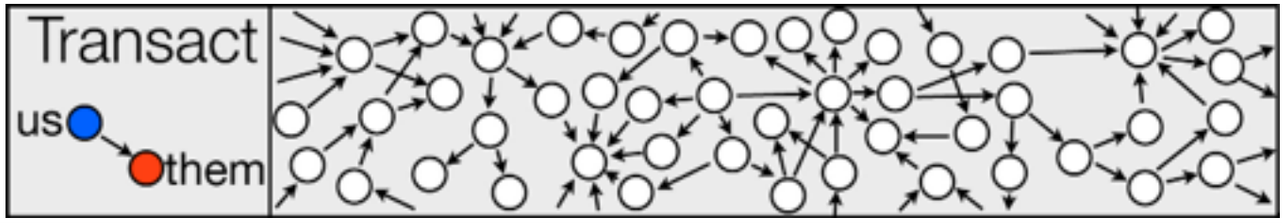
Engaged in transactions with:

- Exchanges
- Vendors
- Mining pools
- Gambling sites
- Wallet services
- Mix services

Scraped published tags

Found addresses discussed on forums

Exchanges



Bitcoin-24

BTC e

aurum exchange

Bitcoin-Central

CAMP BX
BITCOIN TRADING PLATFORM

BitInstant

bitcoin.de
Bitcoin-Marketplace - Made in Germany!

VirtEx
Canadian Virtual Exchange

BITCOIN NORDIC
Bitcoins easy. Bitcoins fast.

Bitcurex
The new age of currency.

ICBIT
Bitcoin Exchange

btcQuick

bitfloor

mercadobitcoin

FastCash4Bitcoins

BitMarket.eu
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MT.GOX

LILION TRANSFER
Login | Registration

BITME

TRADING LTD.
THEROCK

NANAIMO GOLD
DIGITAL CURRENCY EXCHANGE

BITSTAMP

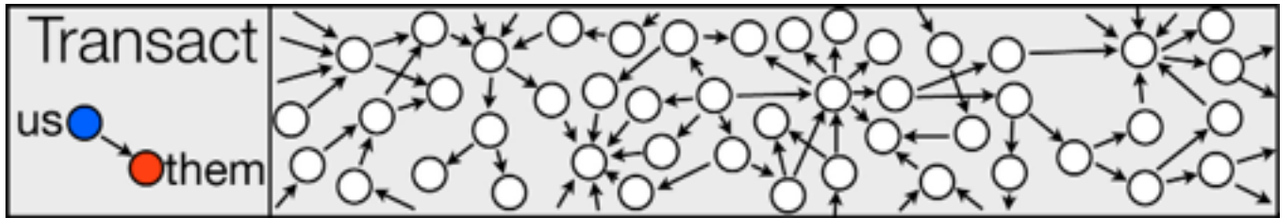
Vircurex

OKPAY payments made easy

Bitcoin China

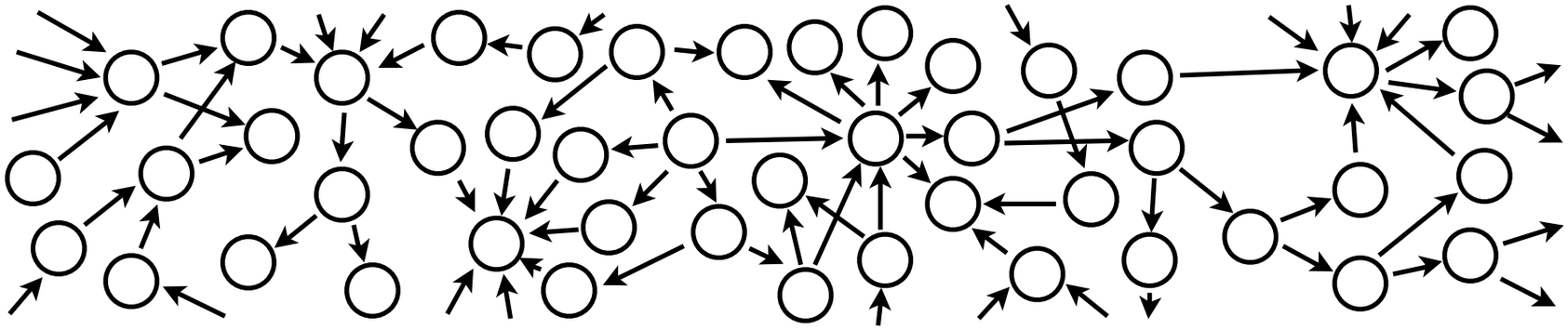
VirWoX
virtual world exchange

Vendors

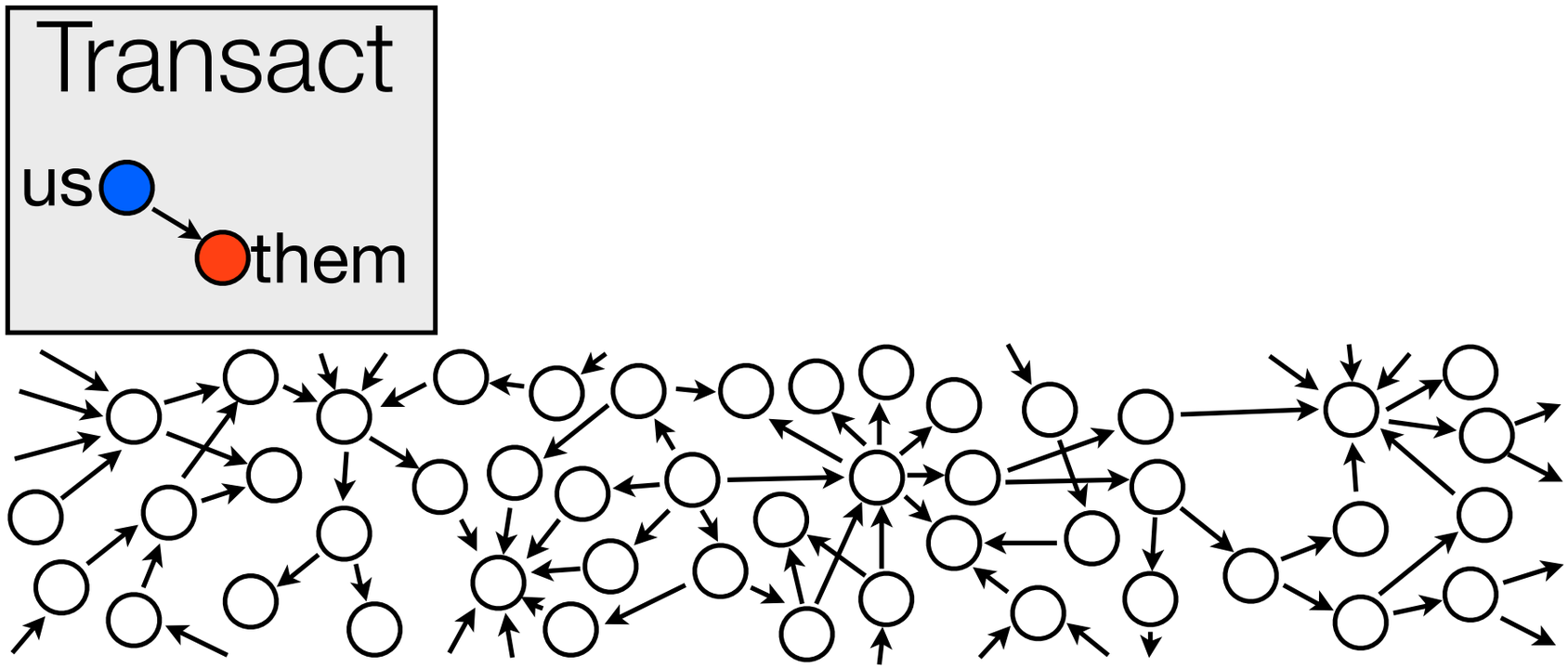

Transact
us
them


SUPER MARIO 3
House
ubuntu
CASIO
Bitcoin
organic colombian latrochela
Bakkav
bitcoin.org
ZYROSTARS
THE LITTLE BOOK OF ANSWERS

Putting it all together



Putting it all together



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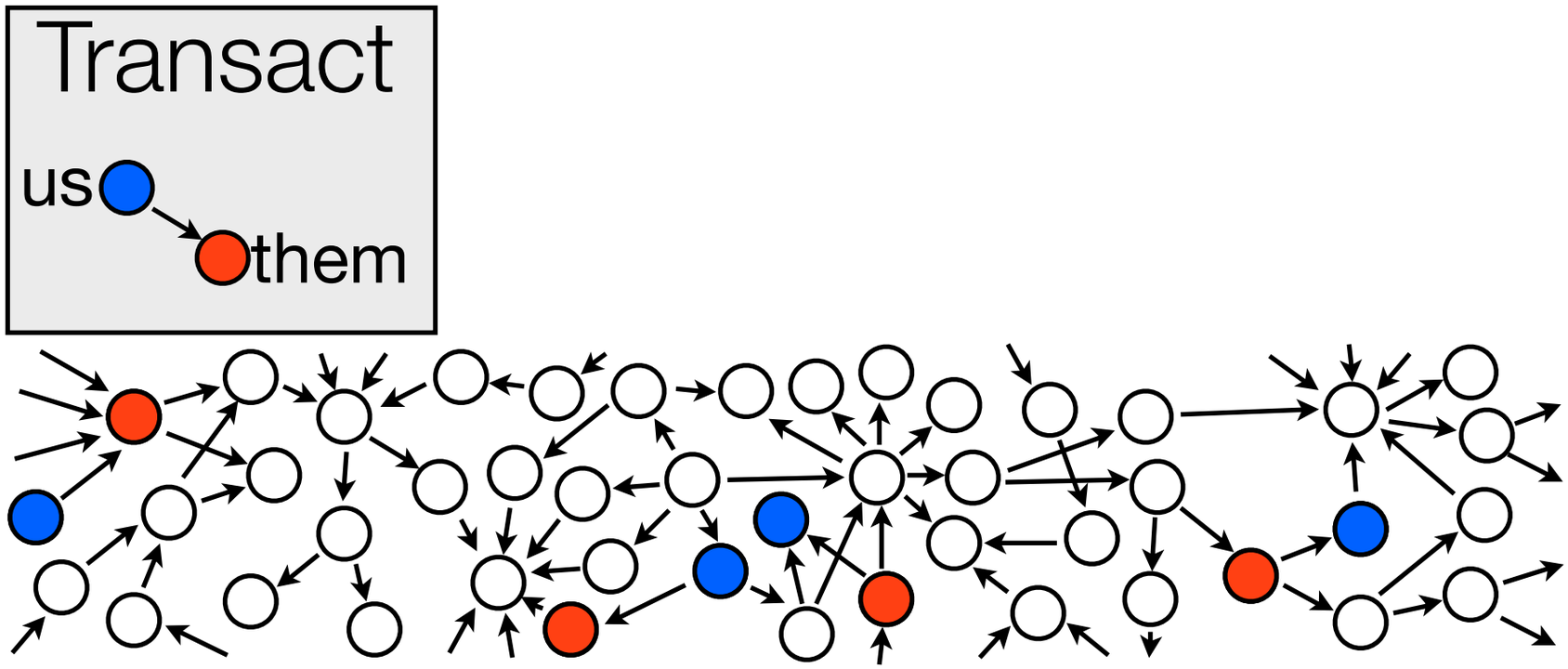

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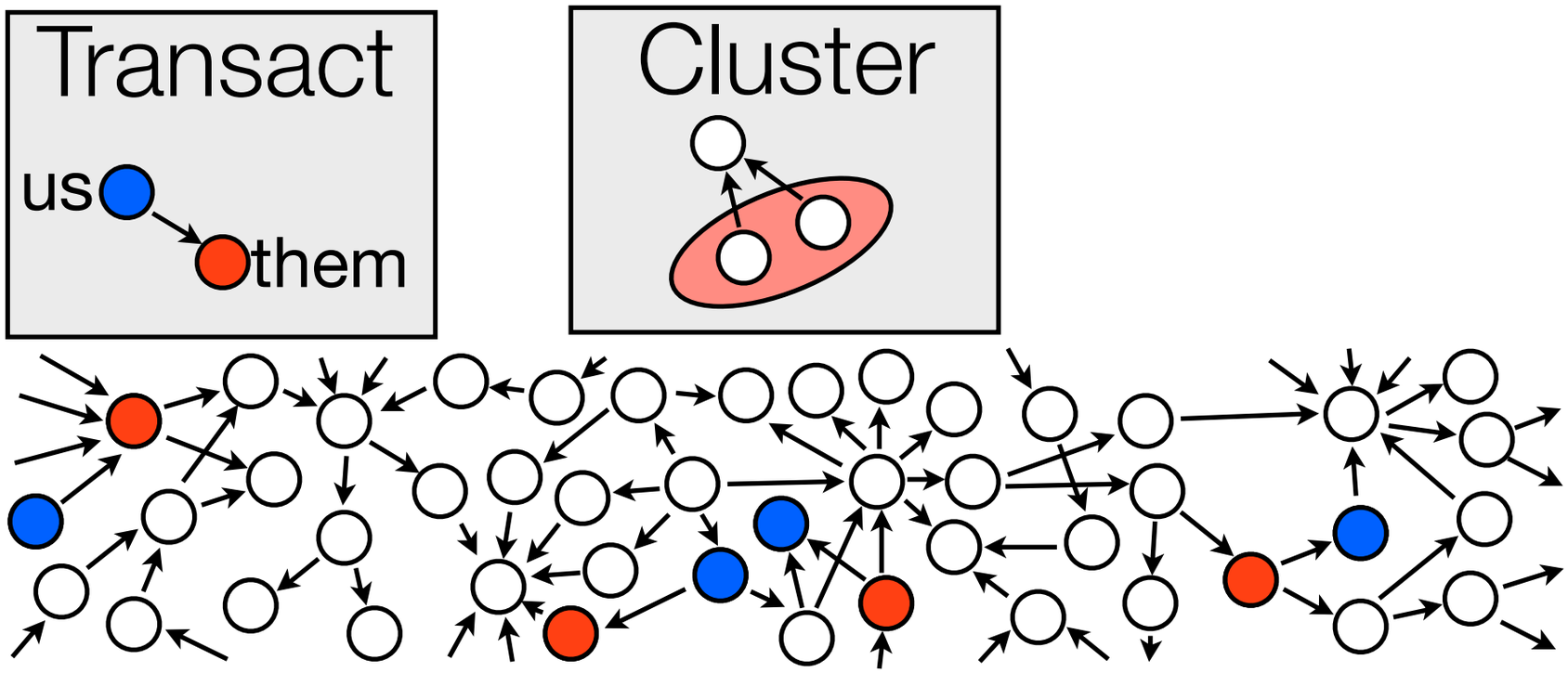
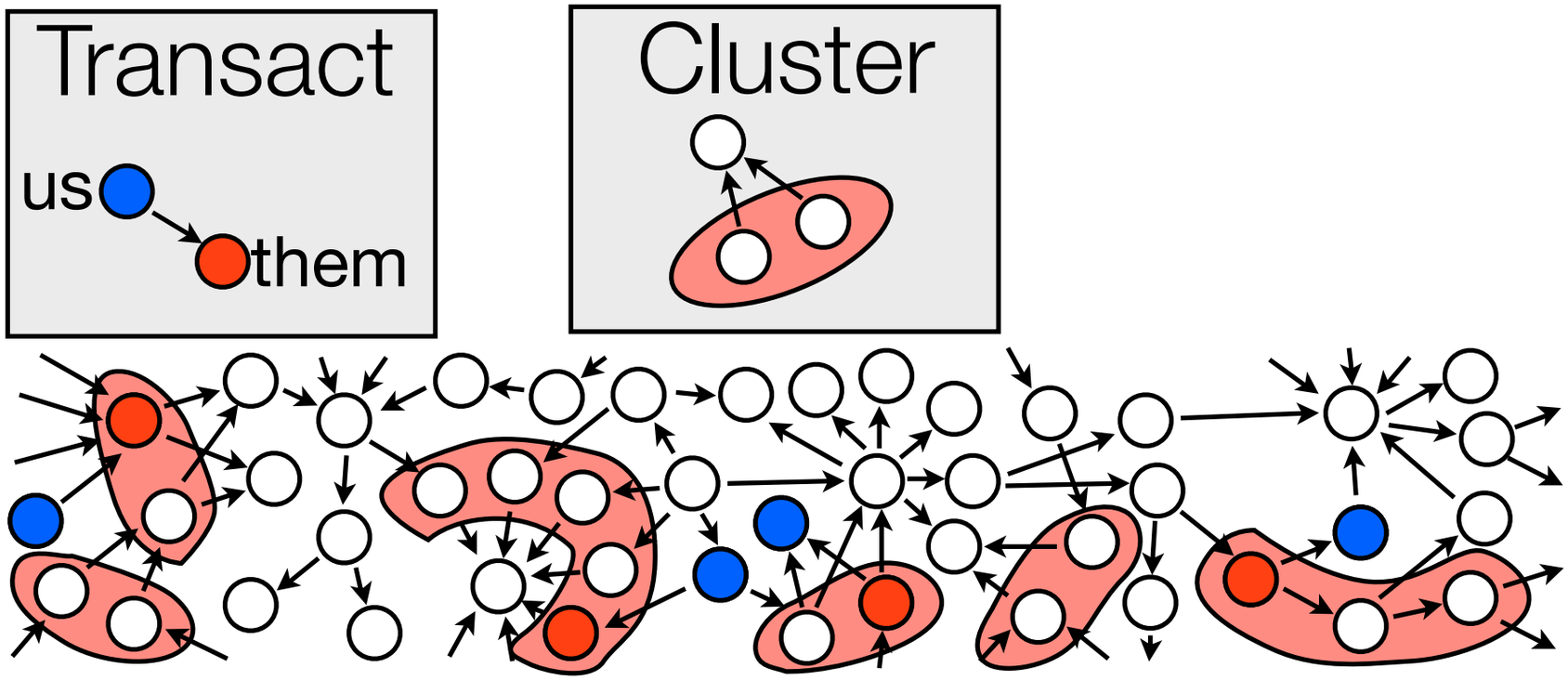
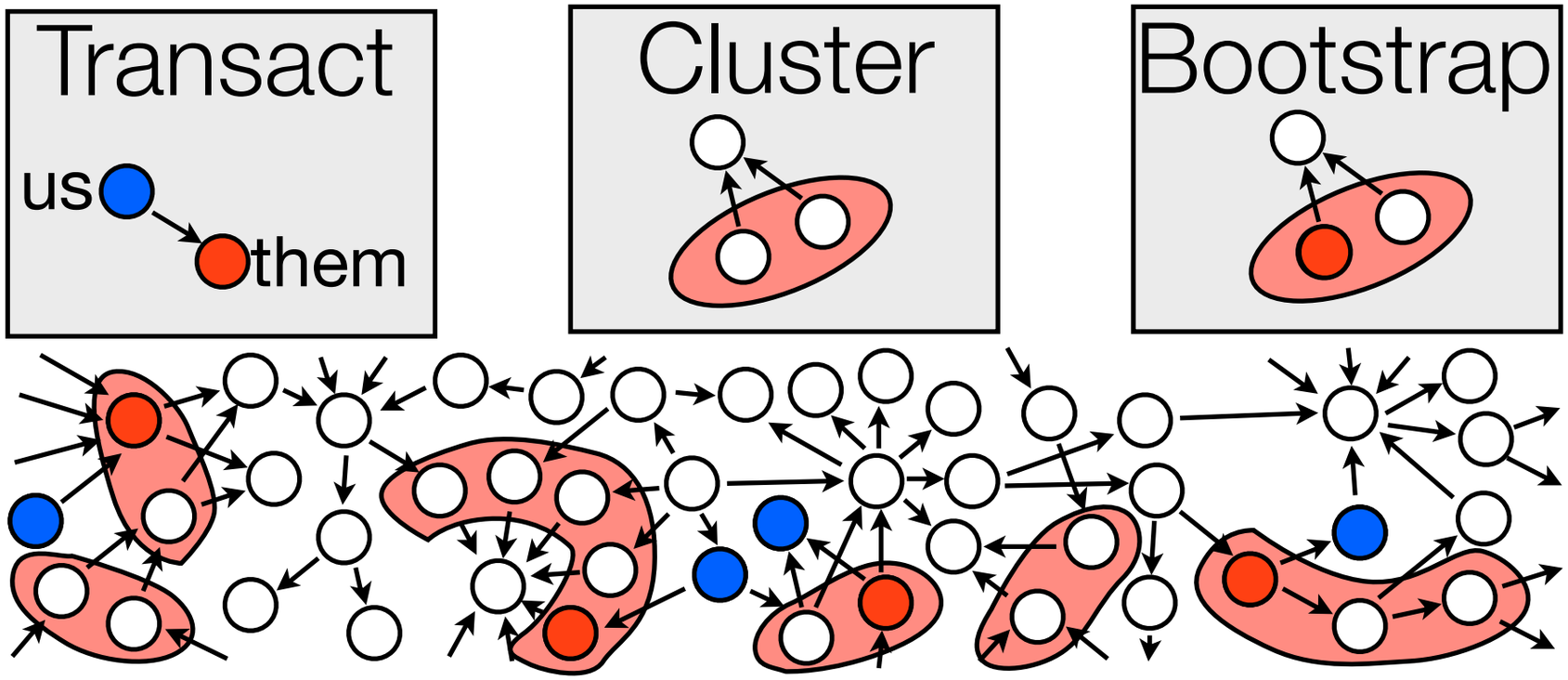


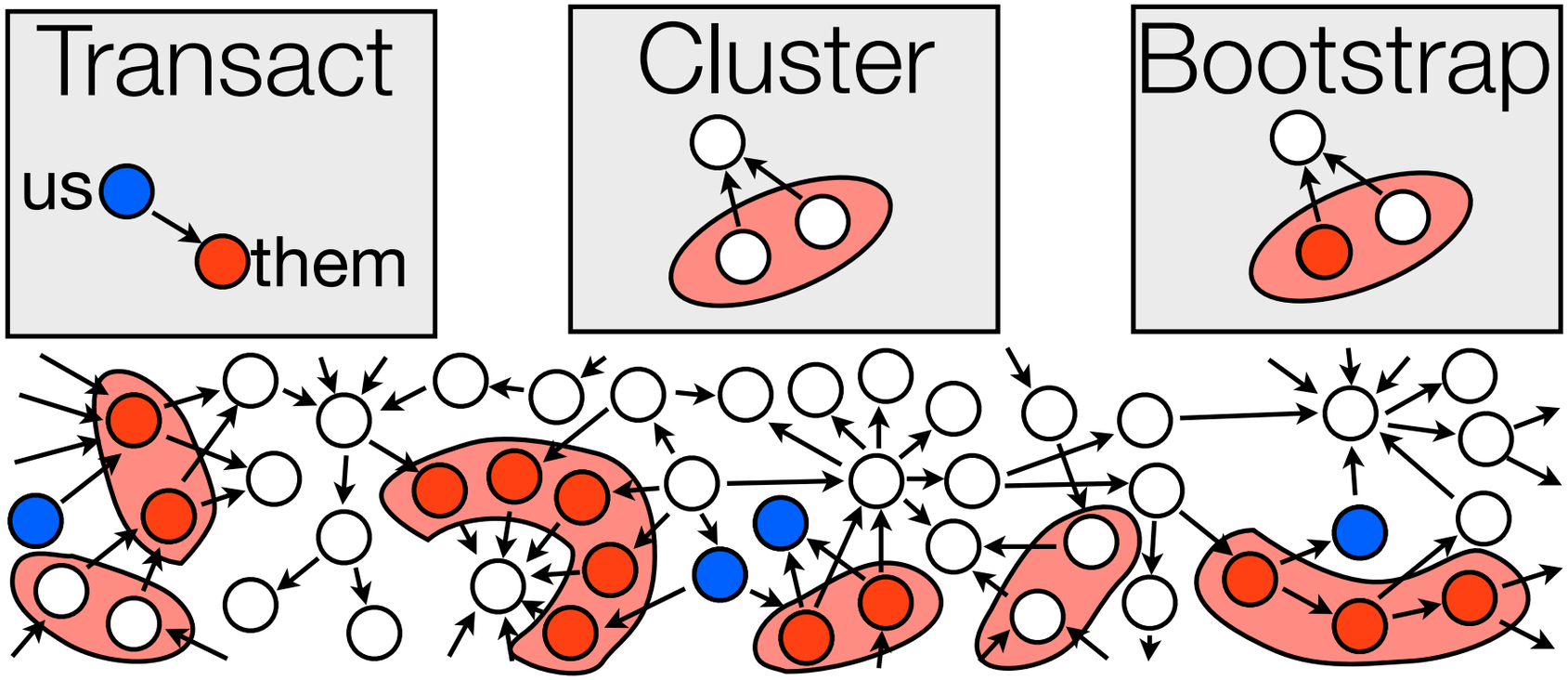
Putting it all together



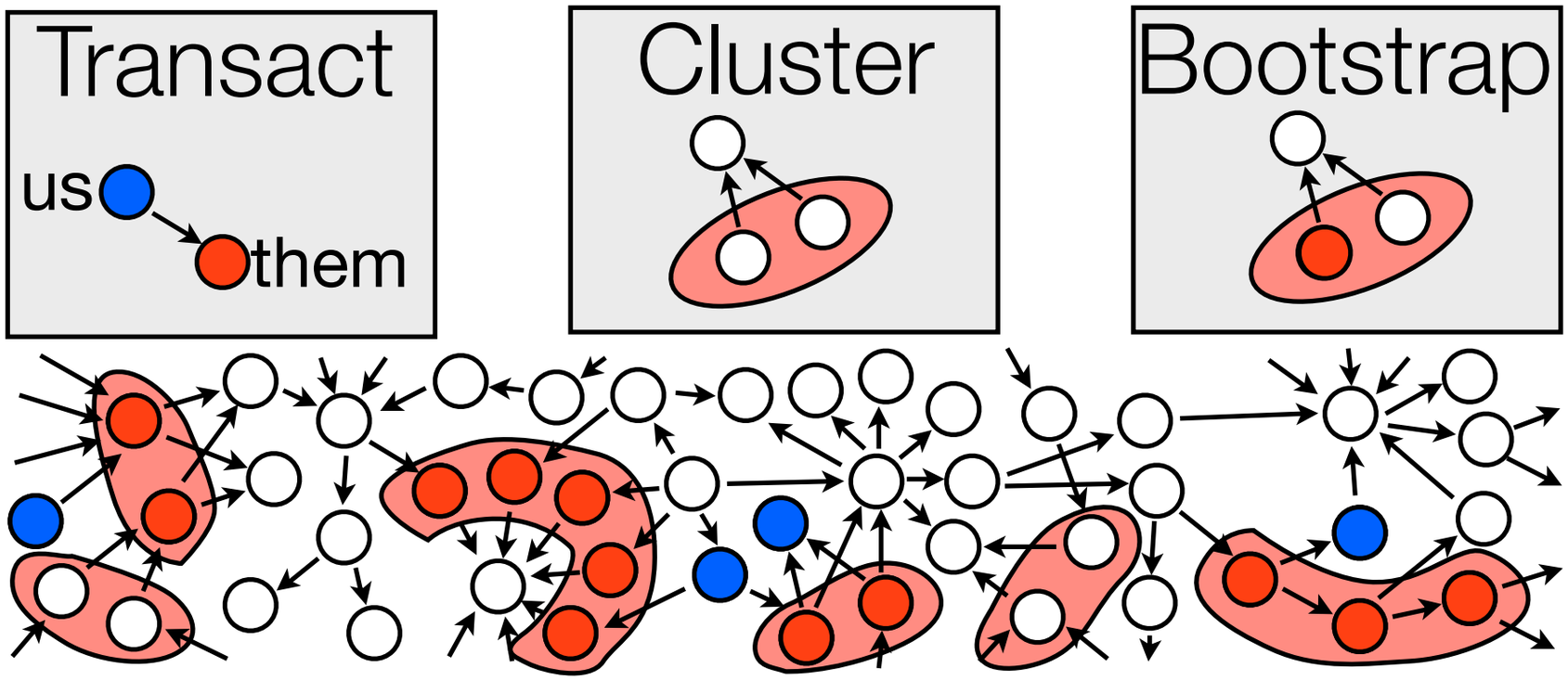
Putting it all together



Putting it all together



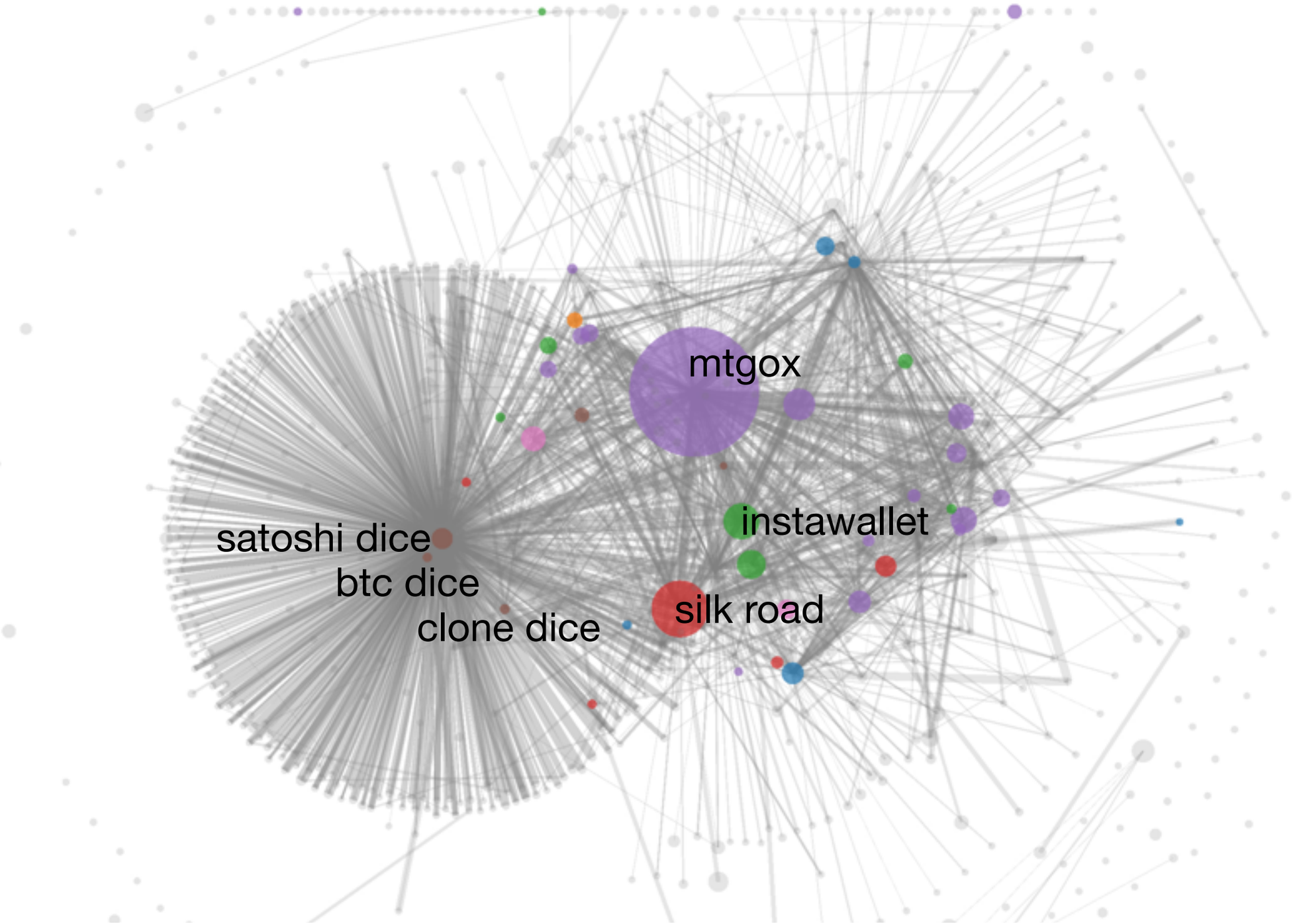
Putting it all together



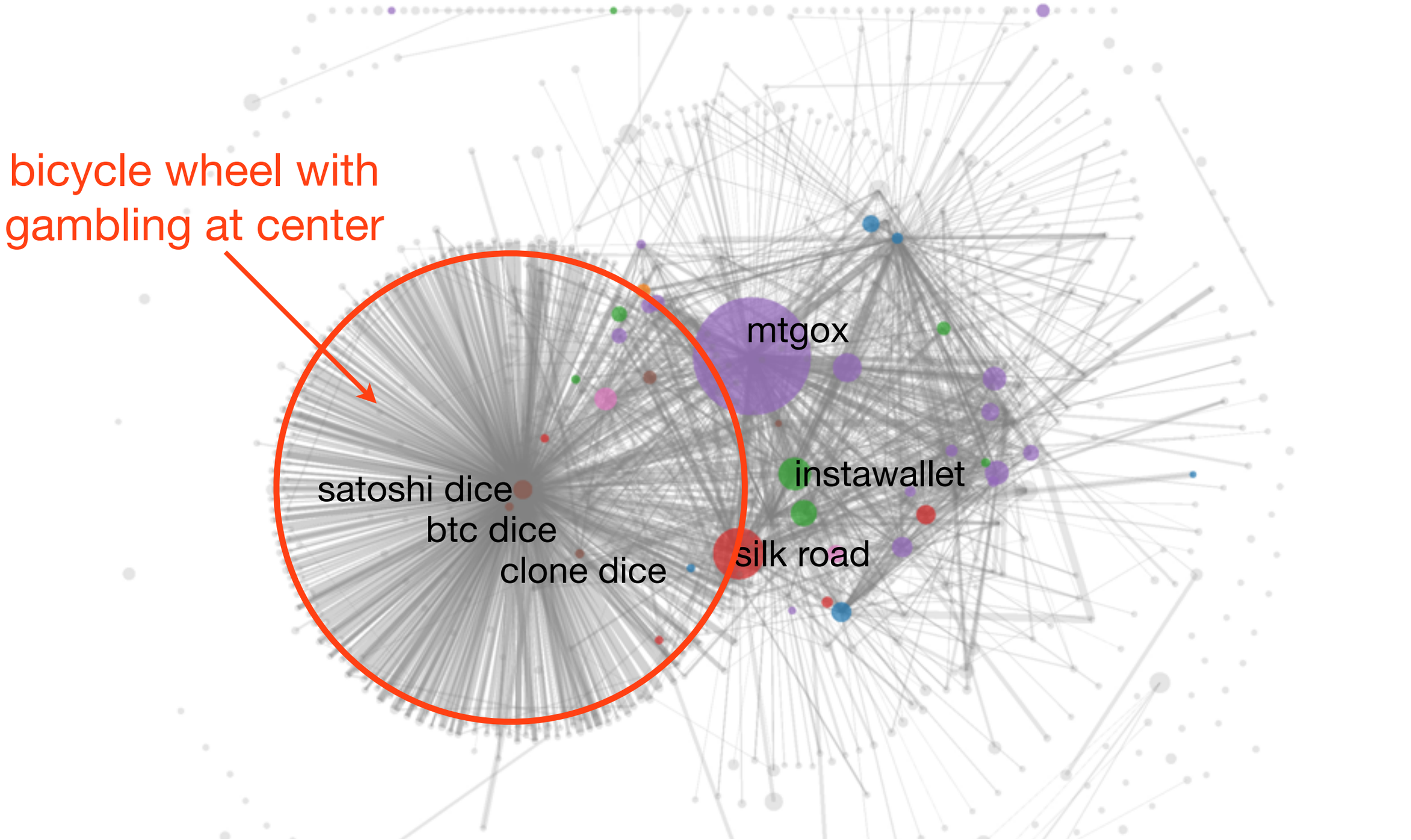
Interacted with 31 MtGox addresses, tagged 518,723!

Participated in 344 transactions and tagged 1.3M public keys

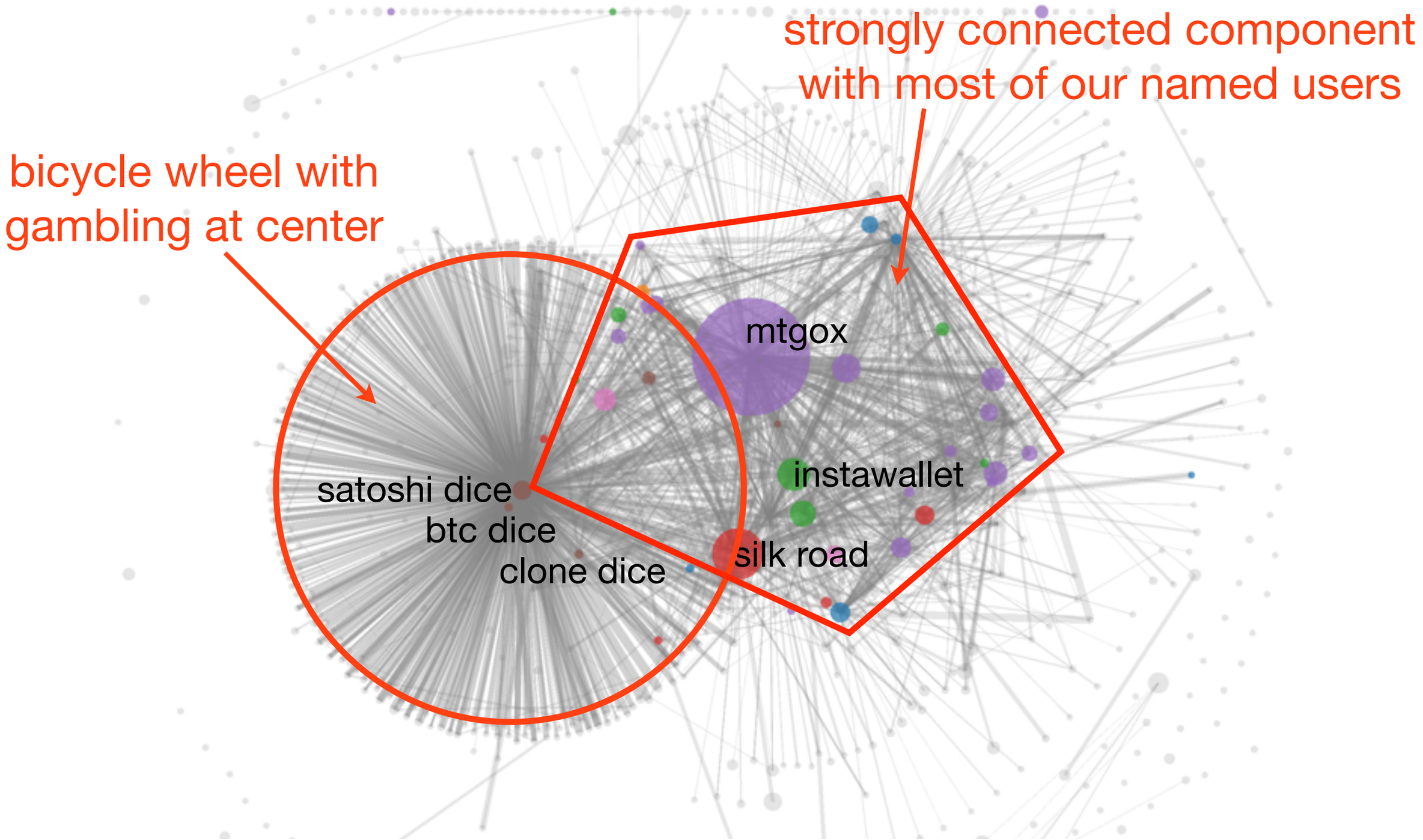
Clustering using Heuristic 2



Clustering using Heuristic 2



Clustering using Heuristic 2



Following bitcoins

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Can see when bitcoins meaningfully cross cluster boundaries

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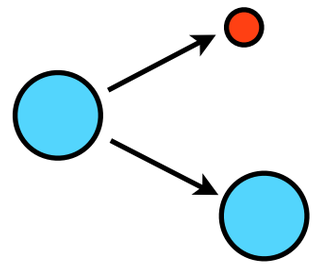

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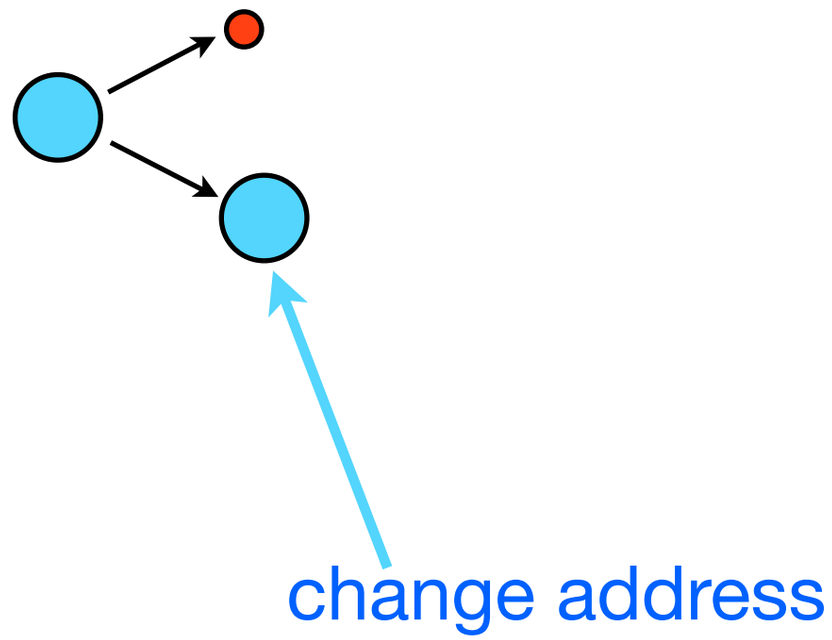

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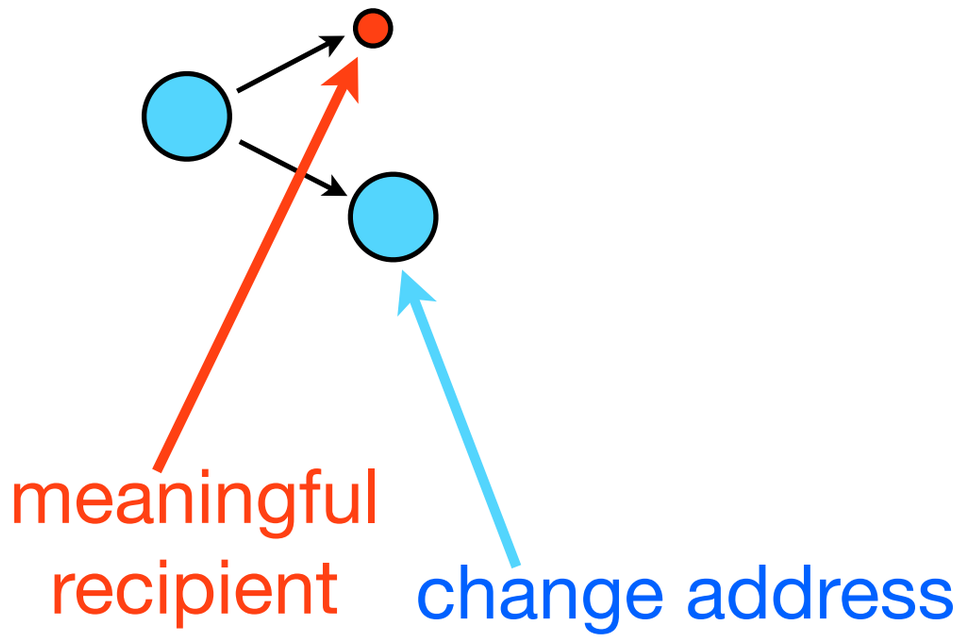

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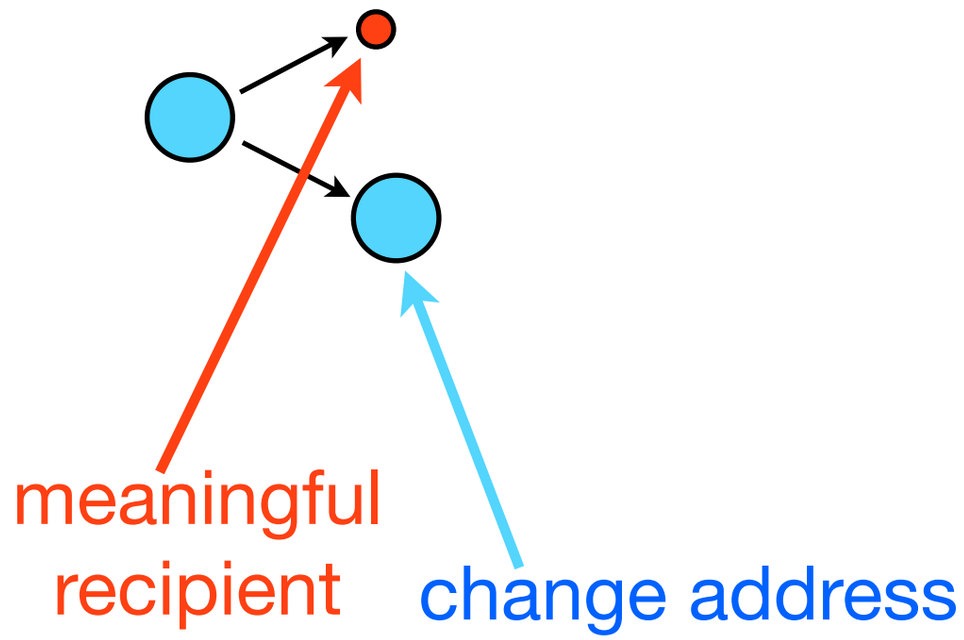
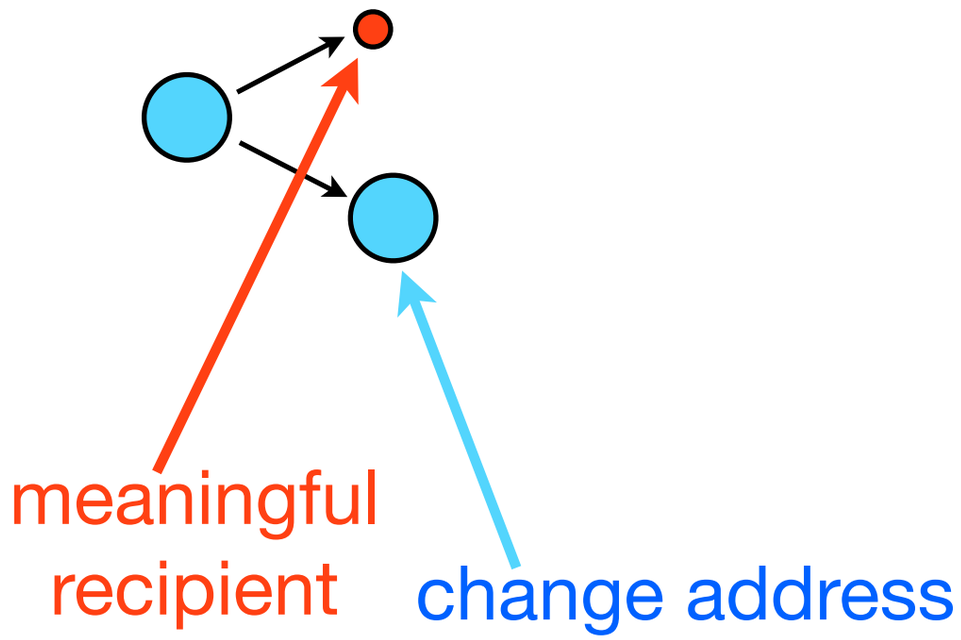


Identifying recipients potentially de-anonymizes user

Following bitcoins

Can see when bitcoins meaningfully cross cluster boundaries



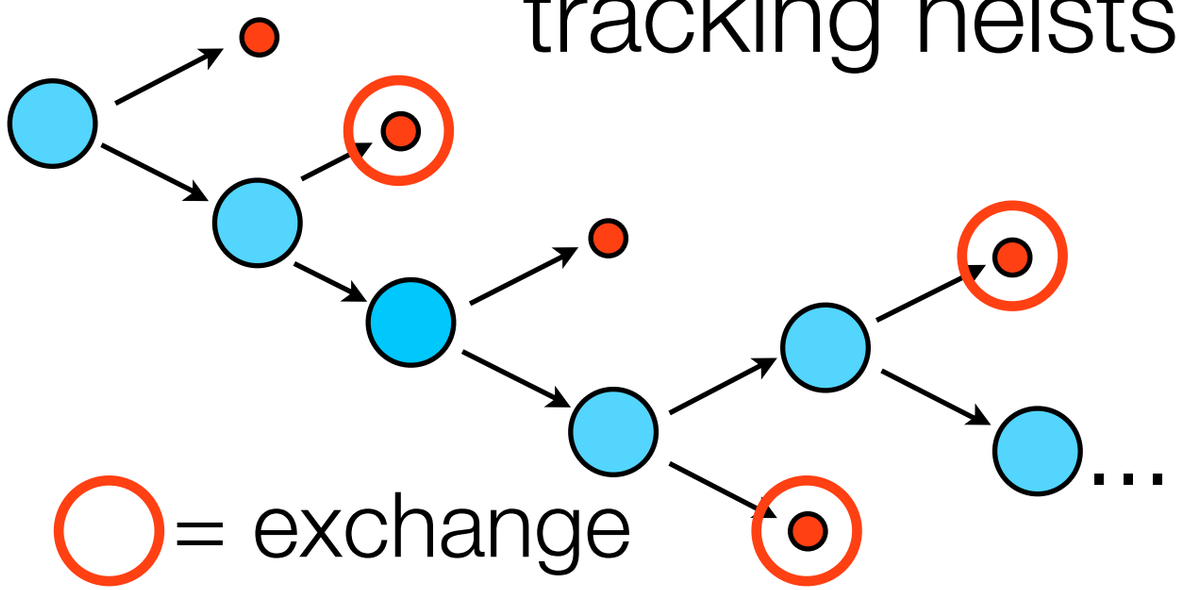
Identifying recipients potentially de-anonymizes user

Hypothesis: if you subpoena exchanges, you can identify users

Tracking technique

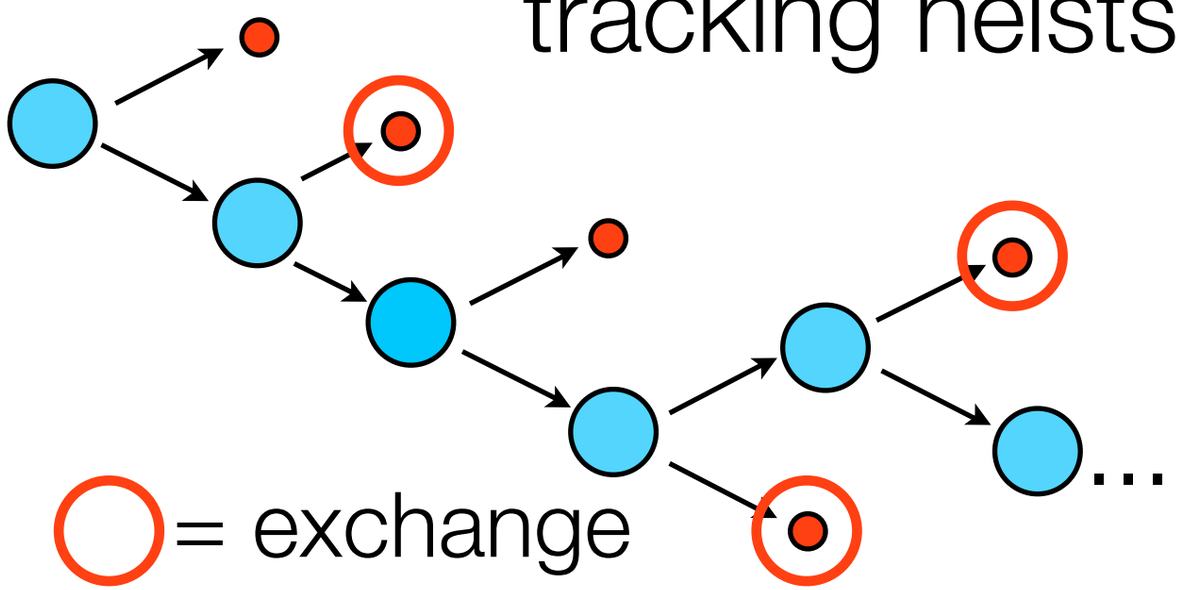
Tracking technique

tracking heists

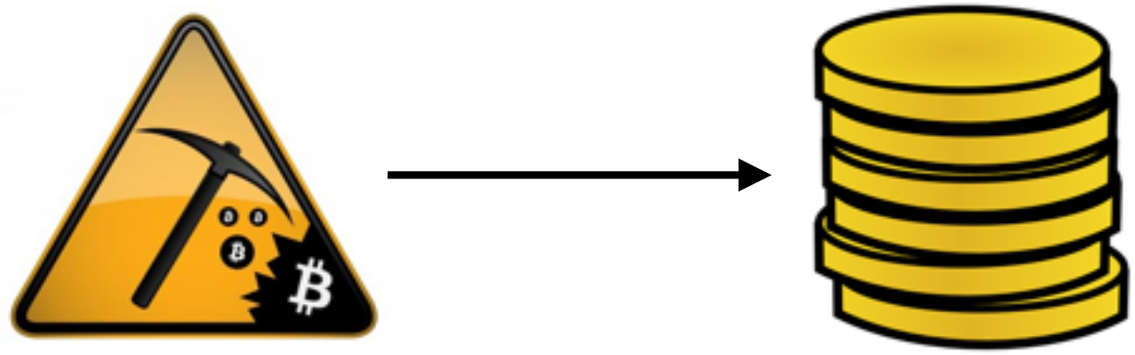


Tracking technique

tracking heists



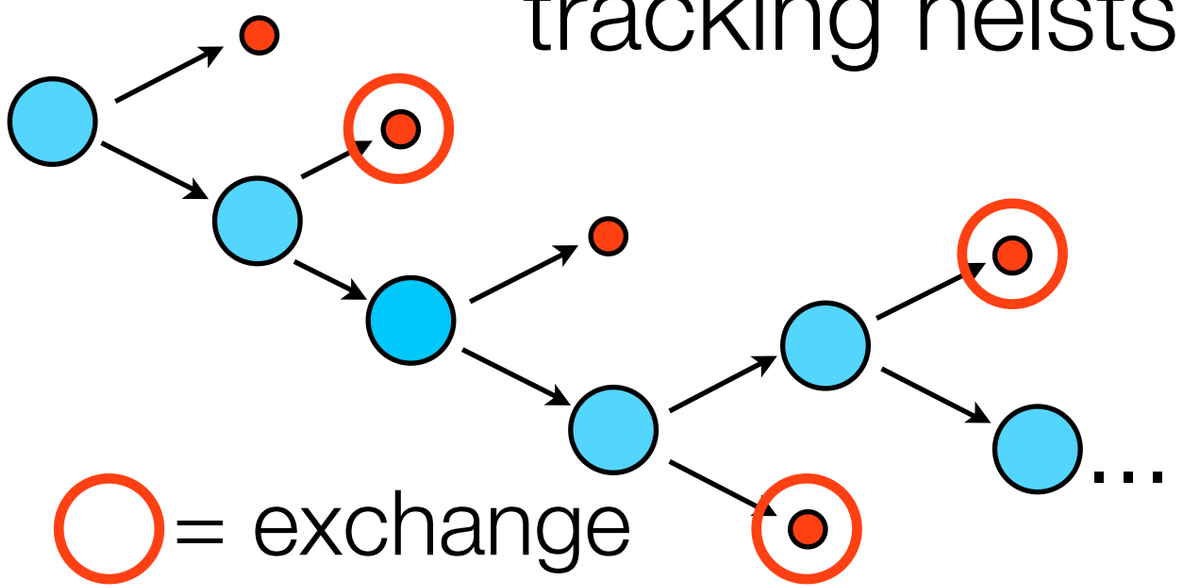
[HD**M**+ NDSS'14]

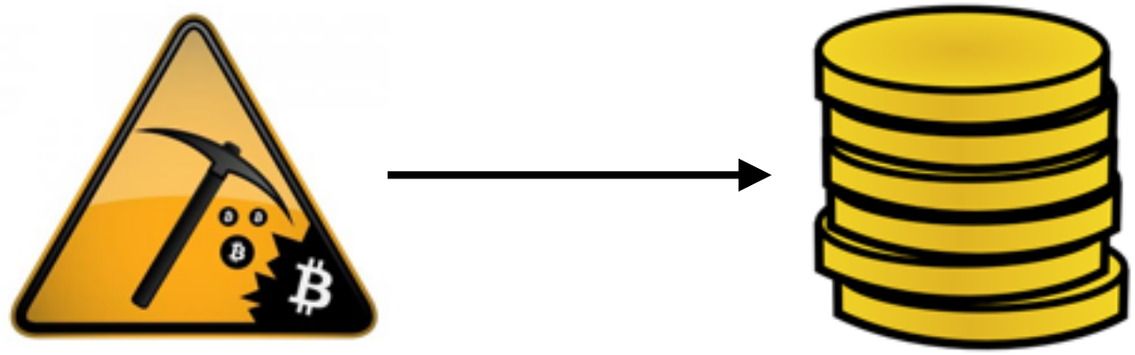


Tracking technique

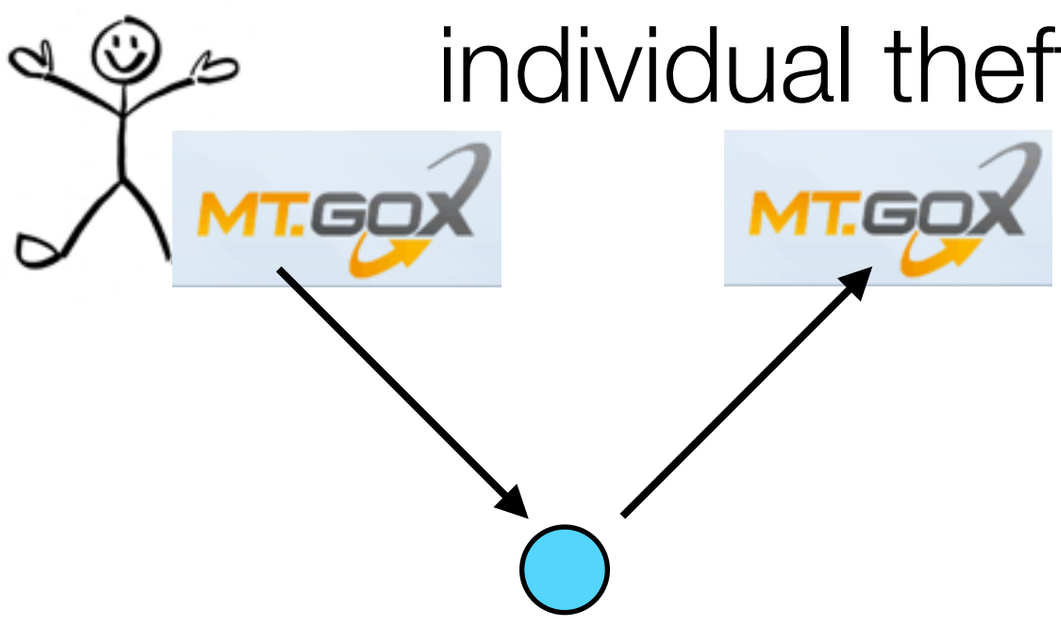
tracking heists

[HD**M**+ NDSS'14]





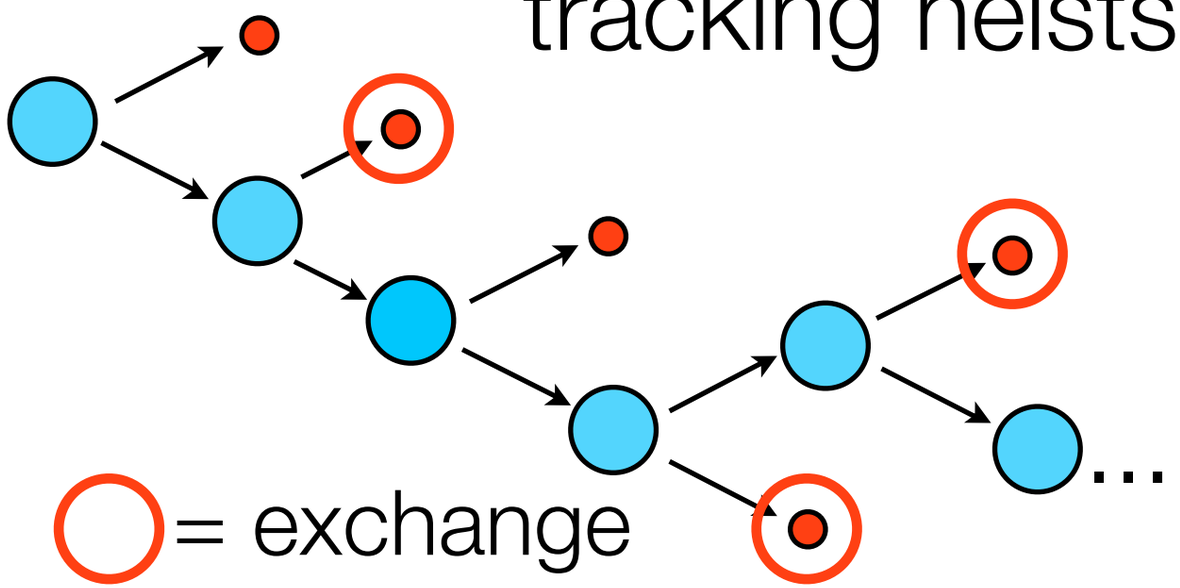
individual thefts

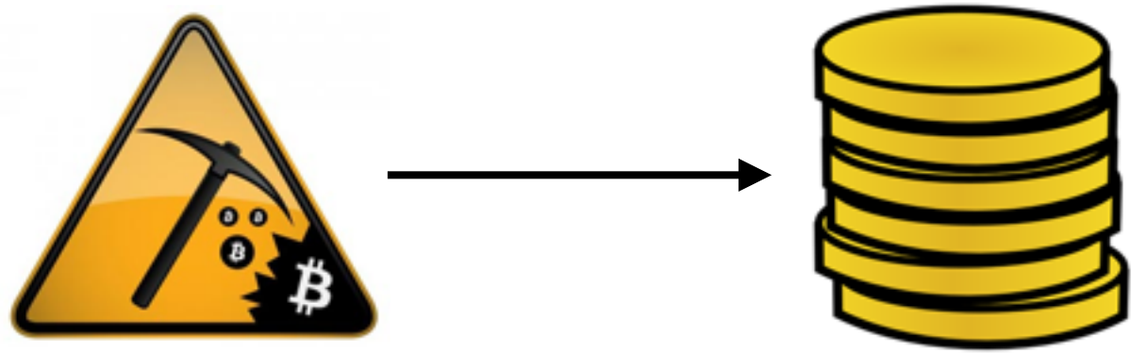


Tracking technique

tracking heists

[HD**M**+ NDSS'14]





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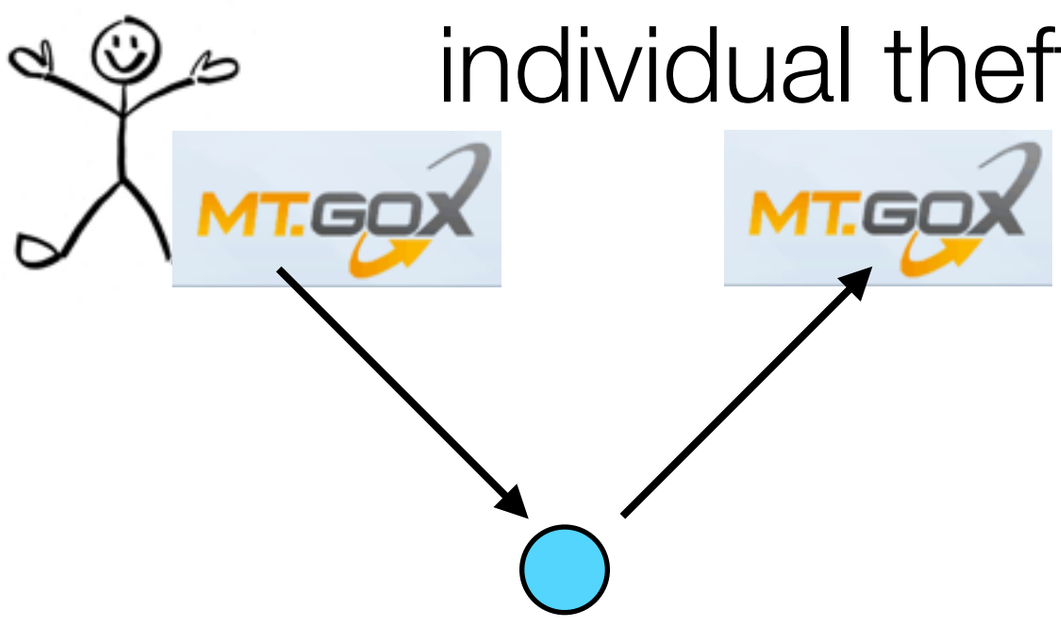

service interaction

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Tracking technique

tracking heists

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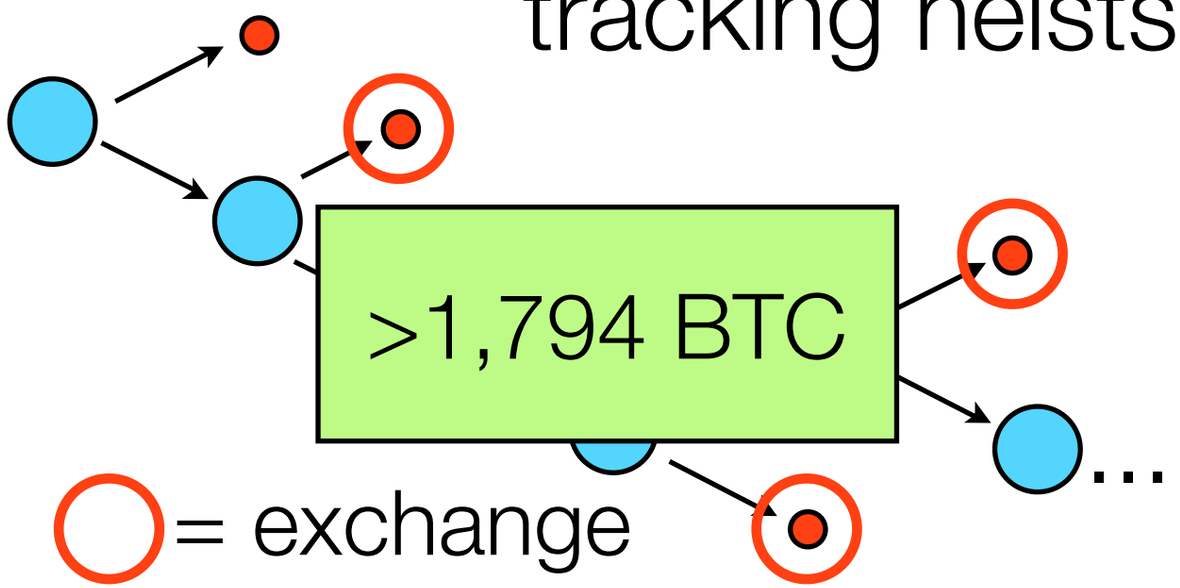
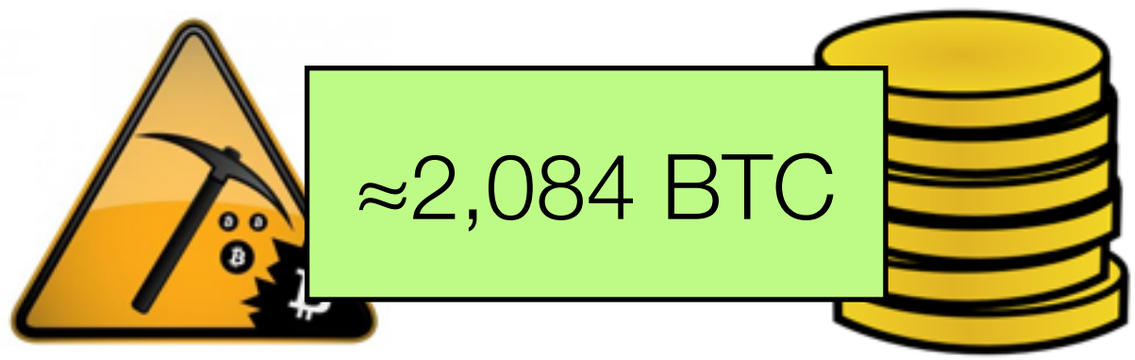
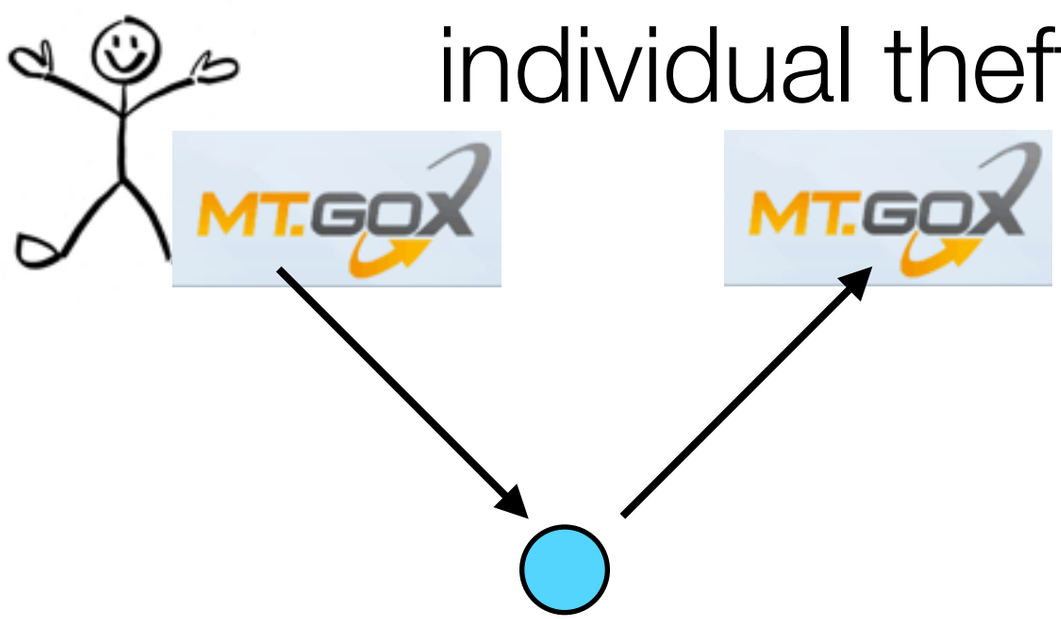




individual thefts



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Takeaway

How much anonymity does Bitcoin really provide?

Takeaway

How much anonymity does Bitcoin really provide?

Our analysis provides a real-world way to track flows of bitcoins

Takeaway

How much anonymity does Bitcoin really provide?

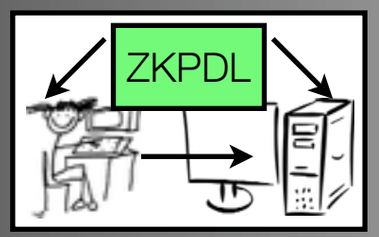
Our analysis provides a real-world way to track flows of bitcoins

Seems hard to launder significant quantities of money

My research

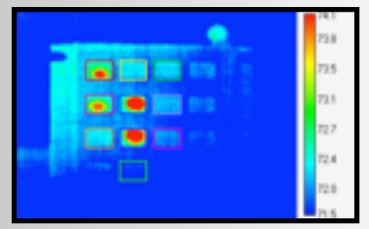

[**M**SF10,L**M**13]


[B**M**T14]



[**M**EKHL10]

[**M**MCS11]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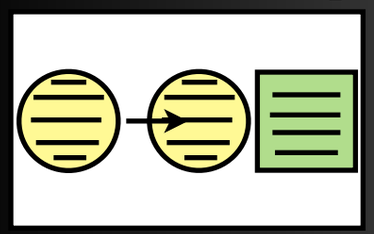
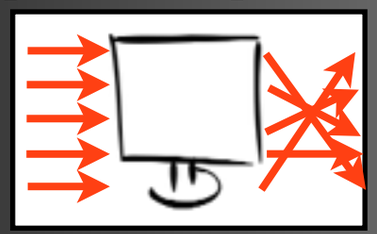
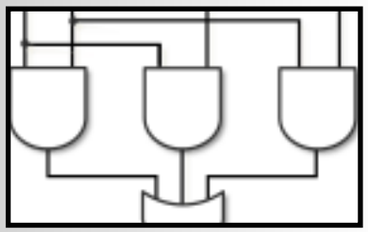

[C**M**14]


[CKL**M**12,13a,13b]

[C**M**Z13]


[**M**P+13,HD**M**+14]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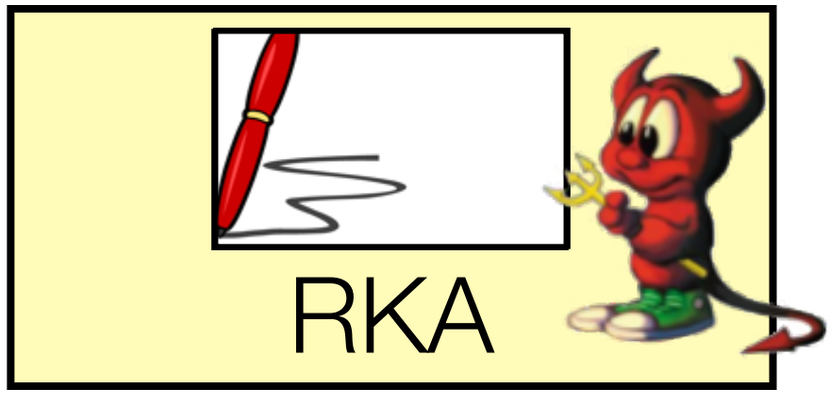

Acknowledgements

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