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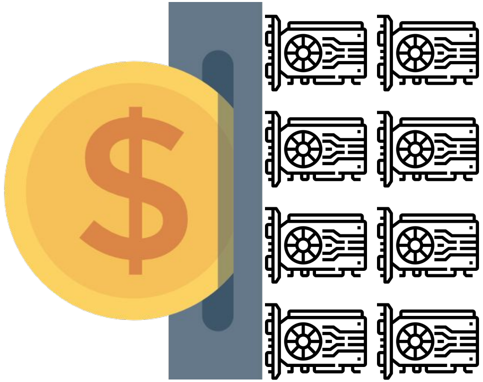
Devcon 5 Research Meetup

11 October 2019, Osaka, Japan

Pay-to-Win

Incentive Attacks on Proof-of-Work Cryptocurrencies



Aljosha Judmayer, Nicholas Stifter, Alexei Zamyatin,

Itay Tsabary, Ittay Eyal, Peter Gazi,

Sarah Meiklejohn, and Edgar Weippl

*“The system is secure as long as **honest** nodes collectively control more CPU power than any cooperating group of attacker nodes.”*

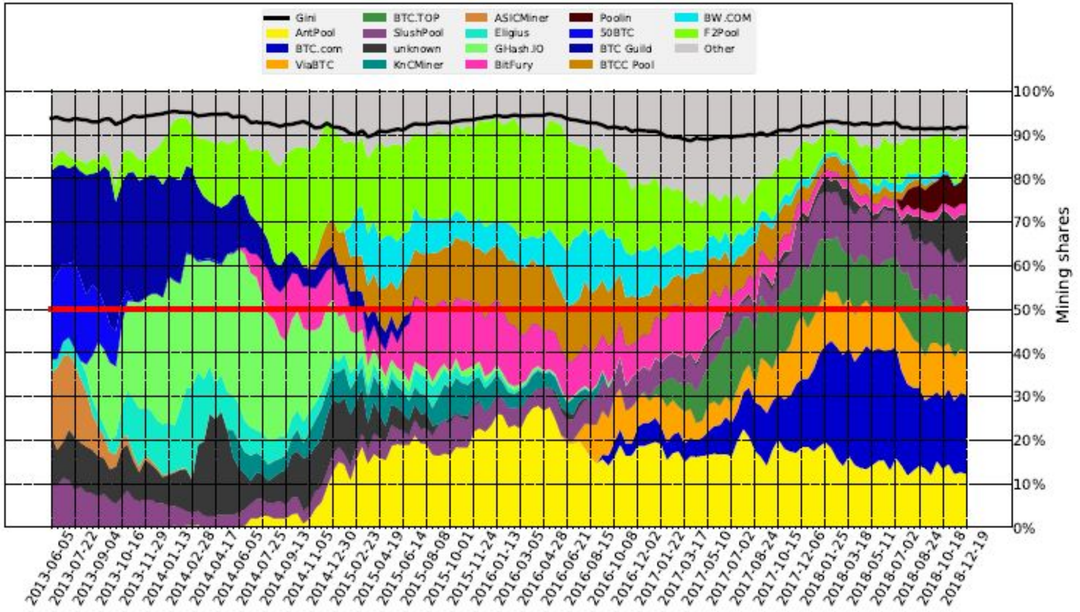
Satoshi Nakamoto

Bitcoin's Security Model

… relies on 2/3 of the computational power being honest

But can we even determine if this is the case?

- Miners can collude
- Can be same entity
- …



A Deep Dive into Bitcoin Mining Pools: An Empirical Analysis of Mining Shares. Romiti M, Judmayer A, Zamyatin A, Haselhofer B. *Workshop on the Economics of Information Security (WEIS)*, 2019

BAR Model

Instead of only honest / dishonest actors, BAR model assumes:

- **Byzantine:** our adversary, behaves dishonestly
- **Altruistic:** altruistic motives, behave honestly
- **Rational:** may deviate from rules to maximize profit

→ **Bribing attacks** assume economically **rational** actors can be bribed into misbehaving

“*Why buy when you can rent?*”

Idea of Bribing attacks:

- Attacker does not need to be a miner
- Offers payment to miners to attack underlying chain
- Ideally: miners do not have to trust the adversary
  - e.g. via smart contracts

Goals:

- Censorship, double spending, reducing active hash rate, destruction on the coin, ...

Recall: States of a Transaction

Unconfirmed	Confirmed	Agreed
TX has been **broadcast** to the network. (*"proposed" or "published"*)	TX has been **included** in a block	TX has been agreed upon, i.e., has ***consensus*** → it has received **k** confirmations and revision is highly unlikely k - security parameter dependent on underlying chain*

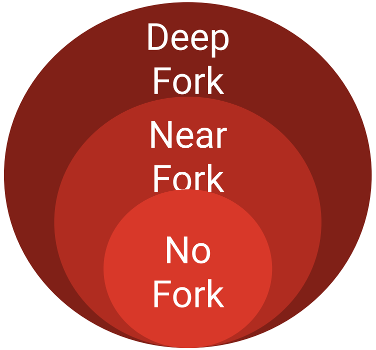
* More about this later

Impact and Required Interference

Impact on Transactions

Revision	Change published, confirmed or agreed TX
Re-ordering	Change ordering of published, confirmed or agreed TX in a block
Exclusion / Censorship	Prevent TX from from being included in the chain (for some period)

Interference with Consensus



- **Deep forks**
  Exceeding the security parameter **k selected by the victim**
- **Near forks**
  Fork, but depth is **not dependent on victim’s k parameter**
- **No forks**

Further Properties

1. Required **attacker hash rate**
2. Required **rational miner hash rate**
3. **Distract hash rate**?
4. **Smart contracts** required?
5. Must the **attacker trust miners**?
6. Must **miners trust the attacker**?
7. Are **failed attacks compensated**?
8. Coordination / payment **in-band or out-of-band (cross-chain)**?
9. …

See paper for more details!

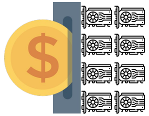
Classification of Incentive Attacks

	Tx rev.	Tx ord.	Tx excl.	Required chain reorganization	Attacker hashrate α	Rational hashrate ω	Distracts hashrate	Requires smart contract	Payment	Trustless for attacker	Trustless for collaborator	Subsidy	Compensates if attack fails
Checklocktime bribes [7]	✓	✗	✗	Deep fork	✗	$\approx [\frac{1}{2}, 1]$	✗	✗	in-band	✓	∼	✗	✗
Whale Transactions [19]	✓	✗	✗	Deep fork	✗	$\approx [\frac{1}{2}, 1]$	✗	✗	in-band	✓	∼	✗	✗
Script Puzzle double-spend [30]	✓	∼	✓	Deep fork	$(0, \frac{1}{2})$	$1-\alpha$	✓	✗	in-band	∼	✗	✗	∼
Script Puzzle 38.2% attack [30]	✗	∼	✓	Near-/No forks	$[0.382, \frac{1}{2})$	$1-\alpha$	✓	?†	out-of-band	?†	?†	✗	✓
Proof-of-Stale blocks [20], [32]	-⋆	-⋆	-⋆	-⋆	✗	-	✓	✓	out-of-band	∼	✓	✗	✓
CensorshipCon [21]	✗	∼	✓	Near-/No forks	$[\frac{1}{3}, \frac{1}{2})$	$[\frac{1}{3}, \frac{2}{3})$	✓	✓	in-band	∼	✗	✓	✗
HistoryRevisionCon [21]	✓	✗	✗	Deep fork	✗	$\approx [\frac{1}{2}, 1]$	✗	✓	in-band	✓	∼	✓	✗
GoldfingerCon [21]	-	-	✓all	No fork	✗	$\approx [\frac{1}{2}, 1]$	✗	✓	out-of-band	✓	✓	✗	✓
Pitchforks [15]	-	-	✓all	No fork	✗	$(\frac{1}{3}, 1]$	✓	✗	out-of-band	✓	✓	✓	✗
Front-running [10], [12]	✗	✓	✗	No fork	✗	$(0, 1]$	✗	✗	in-band	✗	✓	✗	✓
Pay per Miner Censorship [33]	✗	✗	✓	No fork	✗	1	✗	✓	in-band	✓	✓	✗	✗
Pay per Block Censorship [33]	✗	✗	✓	No fork	✗	1	✗	✓	in-band	✓	✓	✗	✓
Pay per Commit Censorship [33]	✗	✗	✓	Near-/No fork	✗	1	✗	✓	in-band	✓	✓	✗	✗
P2W Tx Excl.& Ord.	✗	✓	✓	Near-/No forks	✗	$[\frac{1}{2}, 1]$	✗	✓	out-of-band	✓	✓	✗	✓
P2W Tx Rev. & Excl. & Ord.	✓	✓	✓	Deep fork	✗	$[\frac{1}{2}, 1]$	✗	✓	out-of-band	✓	✓	✗	✓
P2W Tx Ord. Appendix E	✗	✓	✗	No fork	✗	$(0, 1]$	✗	✓	in-band	✓	✓	✗	✗
P2W Tx Excl. Appendix F	✗	✗	✓	Near-/No forks	✗	$[\frac{1}{2}, 1]$	✗	✓	in-band	✓	✓	✗	✗

See paper for more details!

Bribing Myths

“Pfff, bribing is too expensive anyway…”



Risk of failure must be compensated

Existing bribing attacks:

- Payment only if attack succeeds
- Overcompensate risk via **high bribes**

~~“Pfff, bribing is too expensive anyway…”~~

Risk of failure must be compensated

Existing bribing attacks:

- Payment only if attack succeeds
- Overcompensate risk via **high bribes**

Pay-to-Win (This work):

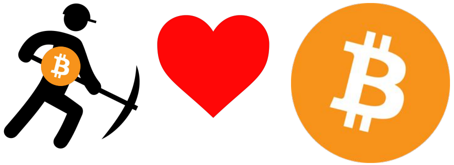
- Always pay miners, even if attack fails
- Miners face no financial risk

→ **only small bribes required**

cheaper than existing attacks

“But miners will not attack their own coin!”

- One of the oldest arguments in this space
- Assumes miners have long term stake in their system



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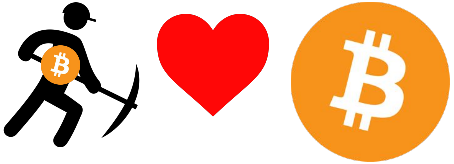
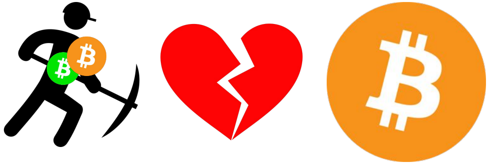


Does not consider:

- Private information



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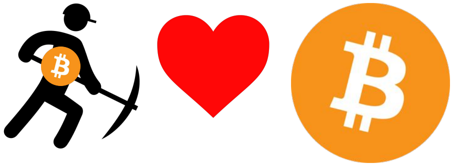

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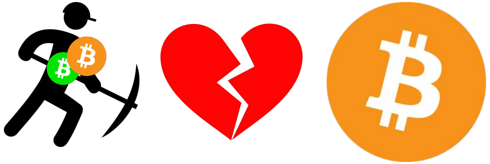
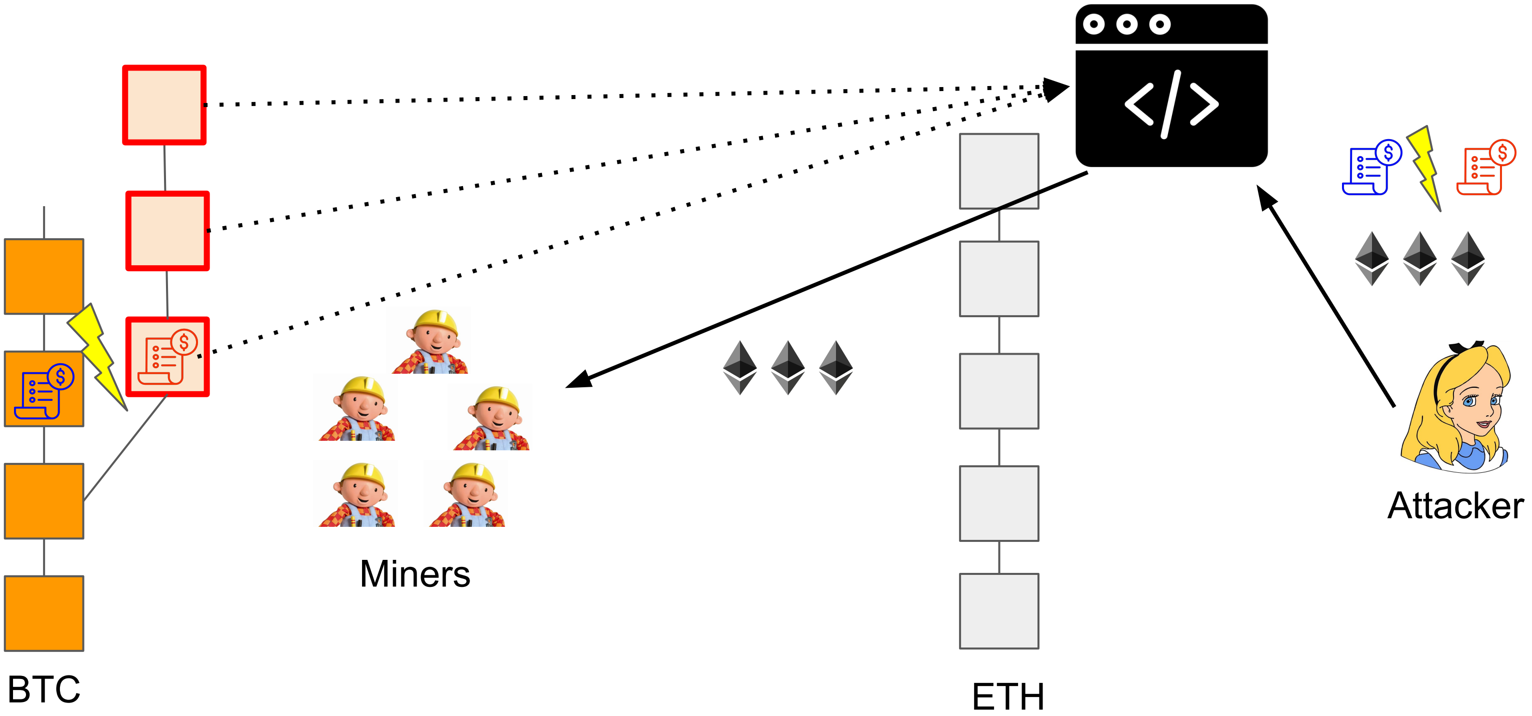


- Cross-chain (“out of band”) attacks **(This work)**

Cross-Chain Bribing Attacks

- **Coordination** and **payout** occur on **another chain**



Cross-Chain Bribing Attacks

- **Coordination** and **payout** occur on **another chain**

  → ***Ephemeral mining relays* (This work)**

  1. **Verify state agreement & evolution** of target chain
  2. **Check validity** of blocks (pre-defined block & TX templates)
  3. **Track forks**
  4. **Check correct execution** of attack
  5. **Handle payouts** depending on outcome

"But is this not too complex and inefficient?"

- **PoW verification needs to be supported by the funding chain!**

~~“But is this not too complex and expensive?”~~

- **PoW verification needs to be supported by the funding chain!**
- PoC implementation of components for attacks on BTC, coordinated on ETH

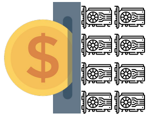
Exaggerated example: 24h attack on Bitcoin (144 blocks)

- Costs to run relay:
  ~ 10-23 USD

- For comparison:
  Value of single BTC block
  (excl. TX fees):
  ~ 77 000 USD

Operation	**Approx. costs**	
	Gas	**USD**
Initialization	244 137	0.21
Block parsing and verification	174 929	0.15
Block header storage	141 534	0.12
Transaction parsing	117 253	0.1
Markle tree verification	80 257 - 194 351	0.07 - 0.16

Gas price: 5 Gwei, Exchange rates as per 10 May 2019 (168.01 USD/ETH)



Pay-to-Win Attacks

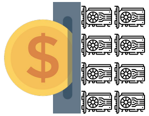
Overview

- Coordination and payouts happen **out-of-band (cross-chain)**
  - *Target* chain (e.g. Bitcoin) vs *funding* chain (e.g. Ethereum)

- Miners are **always compensated** (even for failed attacks)

- Uses **smart contracts on funding chain**
  → **trustless** for attacker and miners!

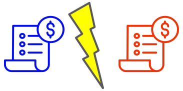
- **2 Variants:**
  - **No / near fork**: ordering and exclusion/censorship
  - **Deep fork**: revision, ordering and exclusion/censorship

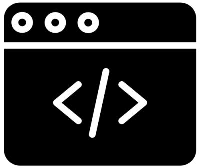


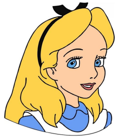
Pay-to-Win Attack (Deep Fork)

Example: double spend on BTC
Attack suceeds if:

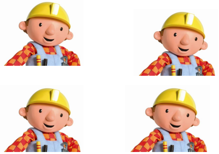
- **> k** blocks on main chain
- **> k+1** blocks on attack chain







Attacker



BTC

Miners

ETH

Pay-to-Win Attack (Deep Fork)

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Attack suceeds if:

- **> k** blocks on main chain
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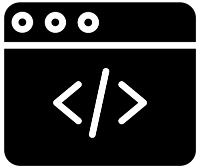
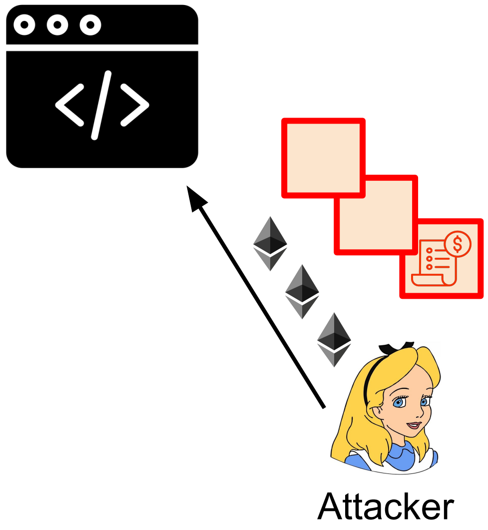


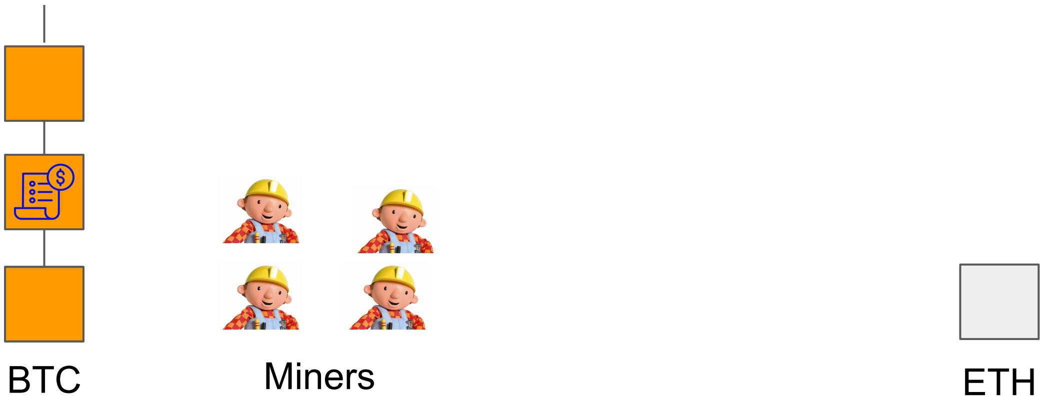
Attacker waits until victim's TX is included and has **k** confirmations (**k** defined by victim)

Pay-to-Win Attack (Deep Fork)

Initialization Phase:
Attacker initializes contract with

- *block templates*→ contain conditions for attack
- *compensation*





Block Templates

Miners can only freely choose:

- *nonce* … for mining iteration
- *coinbase* ... link Ethereum account to block

Block Header

Version
PrevBlockHash
MerkleRoot
Time
nBits
nonce

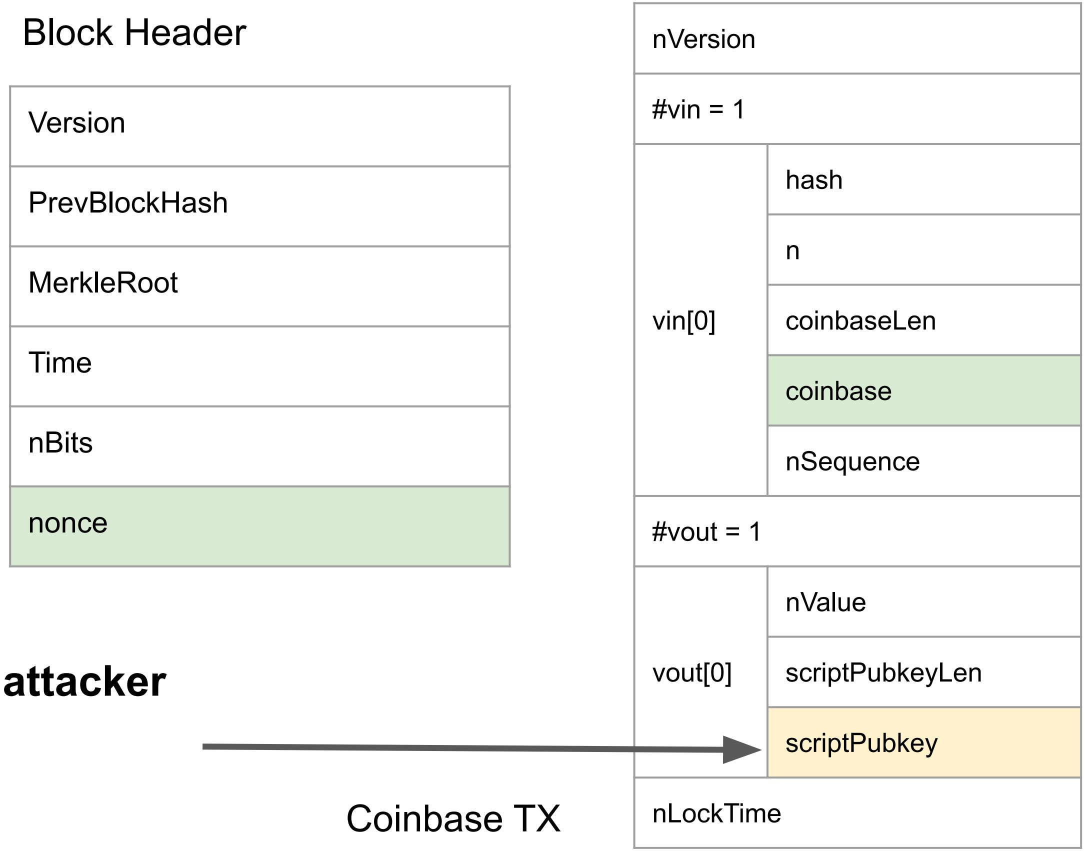
Coinbase TX

nVersion	
#vin = 1	
vin[0]	hash
	n
	coinbaseLen
	coinbase
	nSequence
#vout = 1	
vout[0]	nValue
	scriptPubkeyLen
	scriptPubkey
nLockTime	

Block Templates

Miners can only freely choose:

- *nonce* … for mining iteration
- *coinbase* ... link Ethereum account to block



Note: **BTC block reward must go to attacker** → block reward compensation after the attack ends in ETH

Pay-to-Win Attack (Deep Fork)

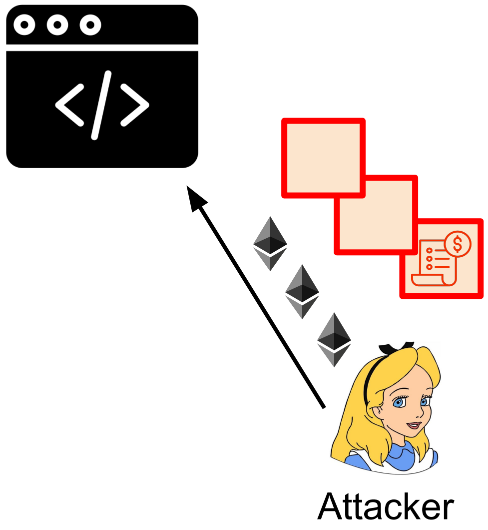
Initialization Phase:

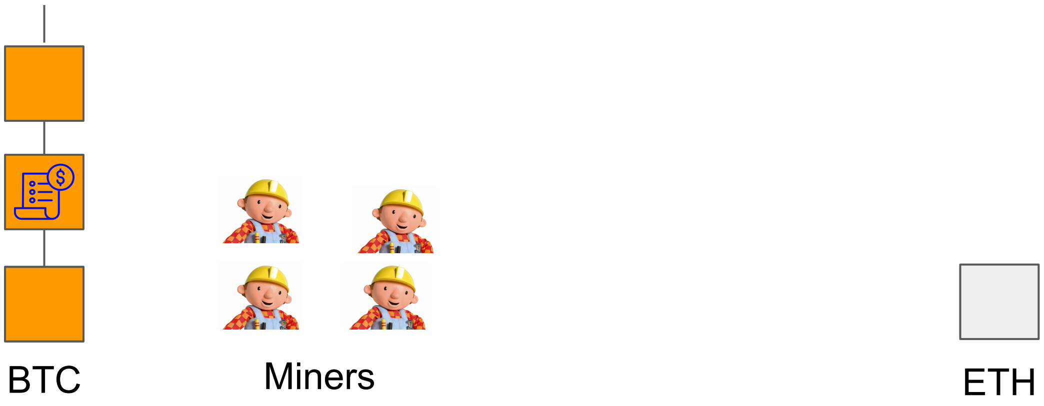
Attacker initializes contract with

- *block templates*→ contain conditions for attack
- *compensation*

Once initialized: **no abort**! (or very high timelock)

→ Reason: race conditions

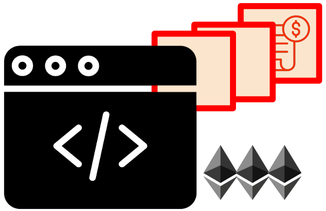


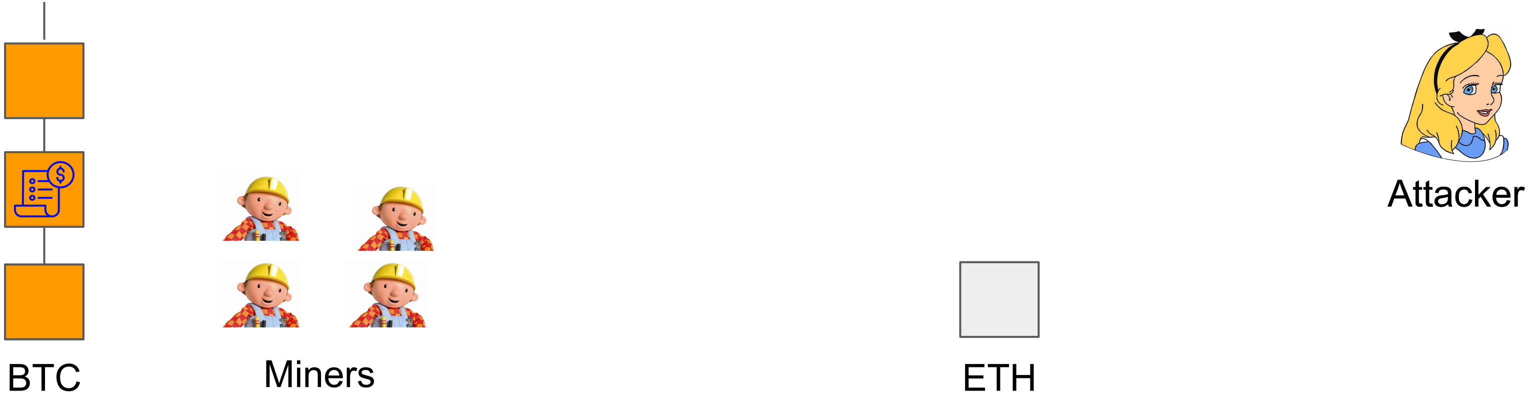


Pay-to-Win Attack (Deep Fork)

Attack Phase:

- Miners mine on block templates, executing the attack
- Attacker can extend the attack (new templates + funds)

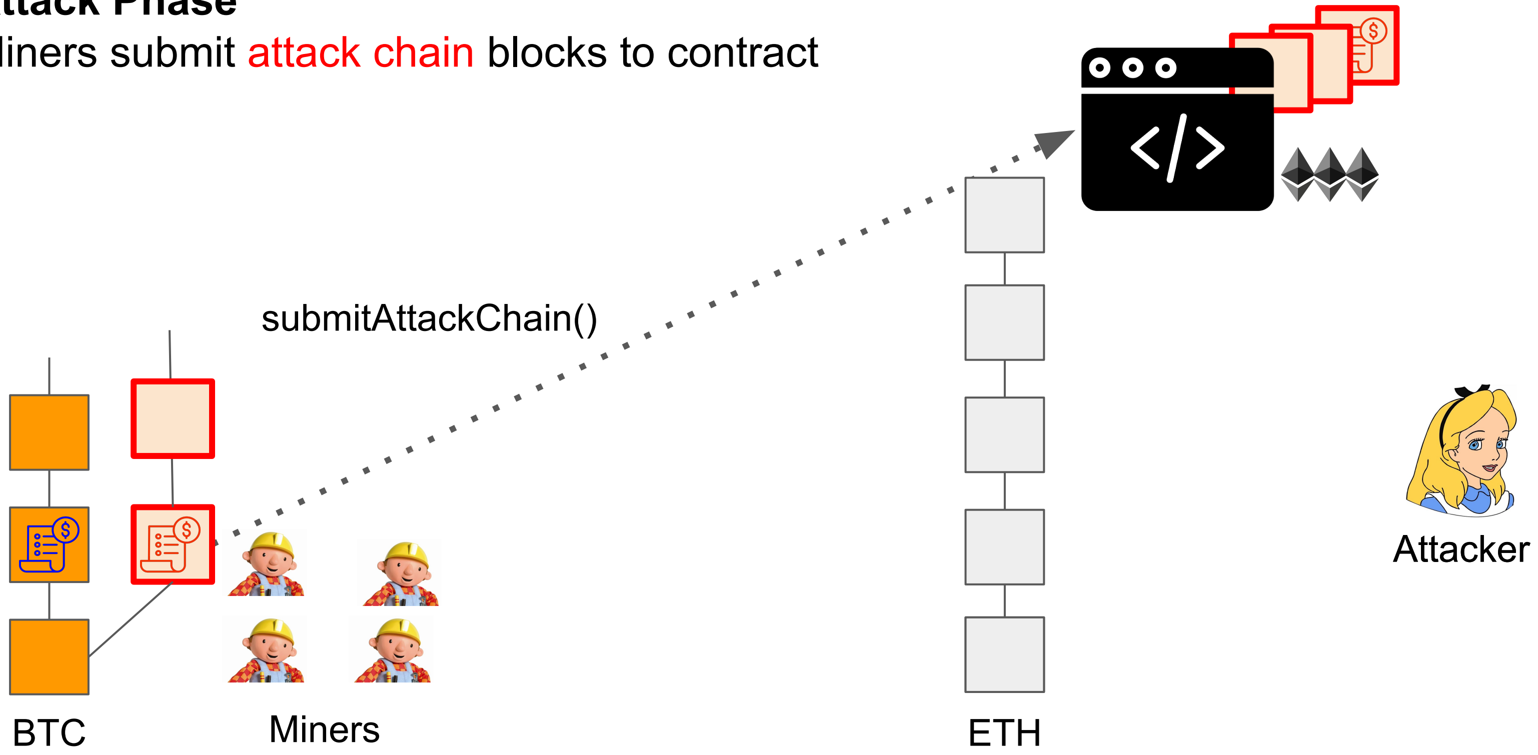




Pay-to-Win Attack (Deep Fork)

Attack Phase

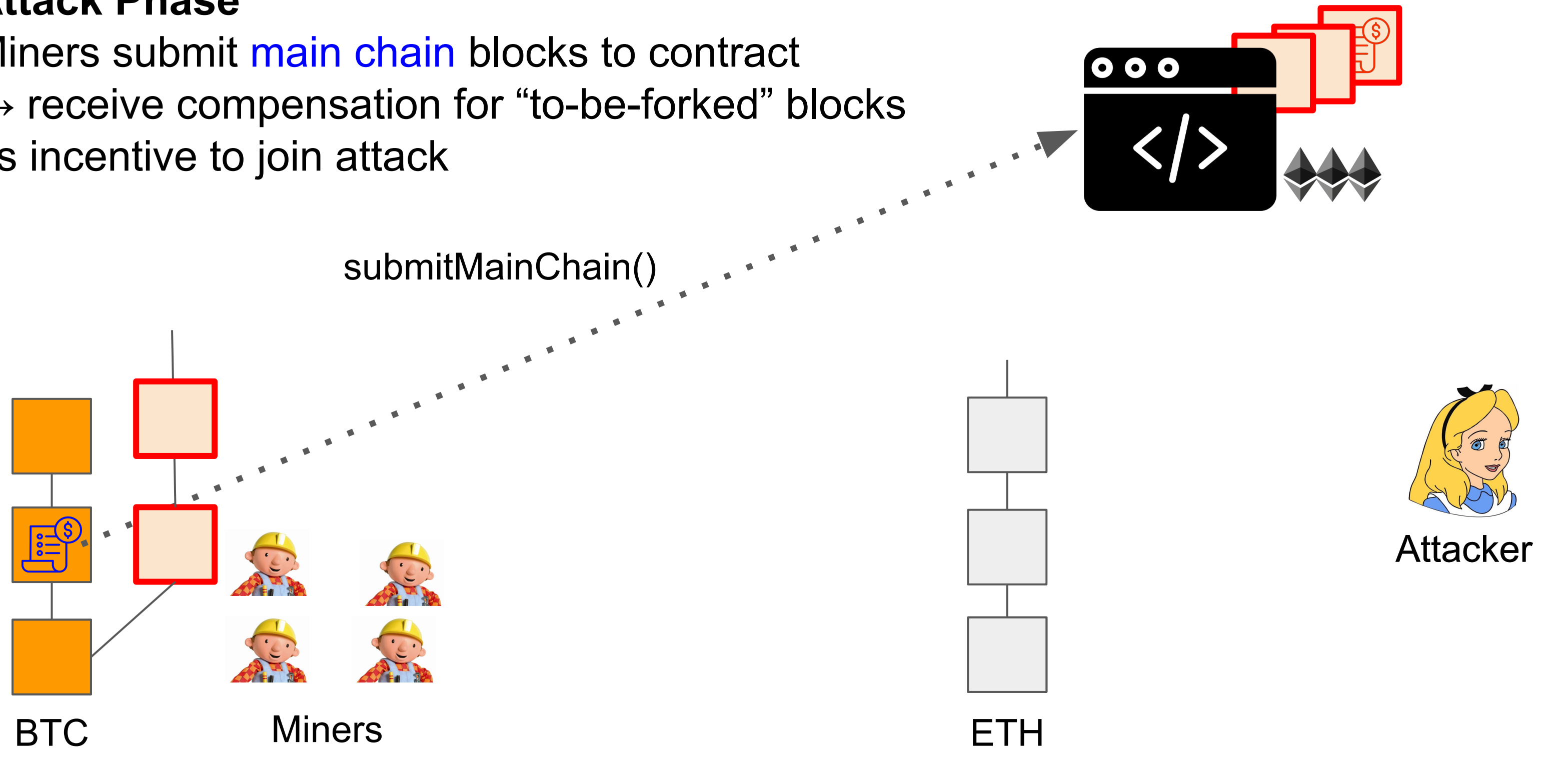
Miners submit attack chain blocks to contract



Pay-to-Win Attack (Deep Fork)

Attack Phase

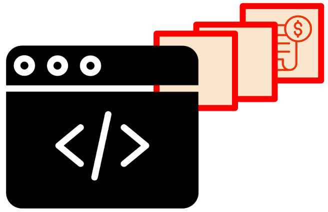
Miners submit main chain blocks to contract
→ receive compensation for “to-be-forked” blocks
as incentive to join attack

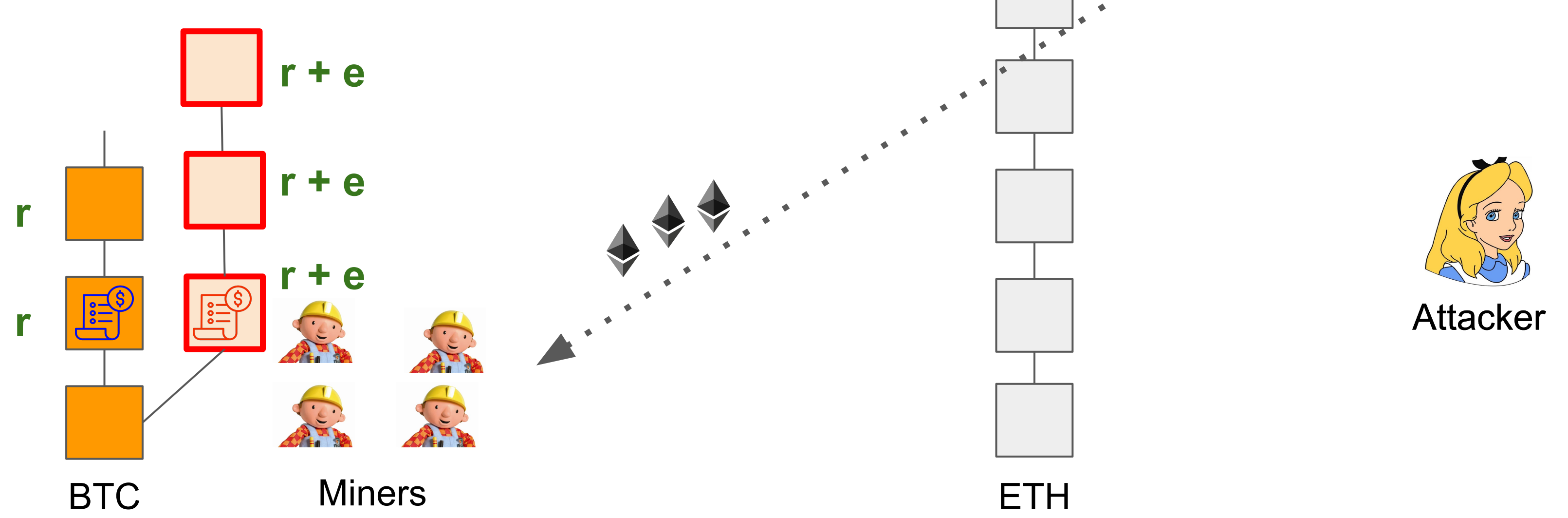


Pay-to-Win Attack (Deep Fork)

Payout Phase: **Successful attack**

- **Block rewards (r)** for k main chain blocks
- **Block reward + bribe (r + e)** for attack chain blocks



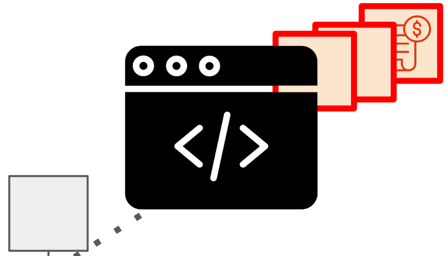


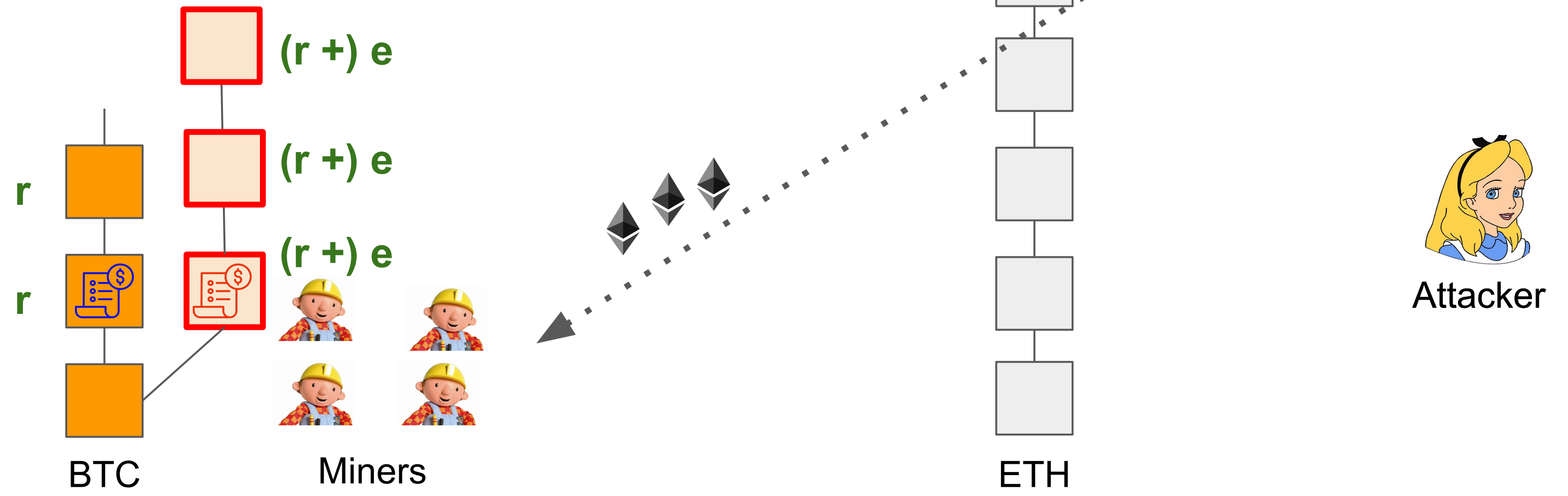
Pay-to-Win Attack (Deep Fork)

Payout Phase: **Successful attack**

- **Block rewards (r)** for k main chain blocks
- **Block reward + bribe (r + e)** for attack chain blocks

→ **Recall**: attacker receives BTC block reward!

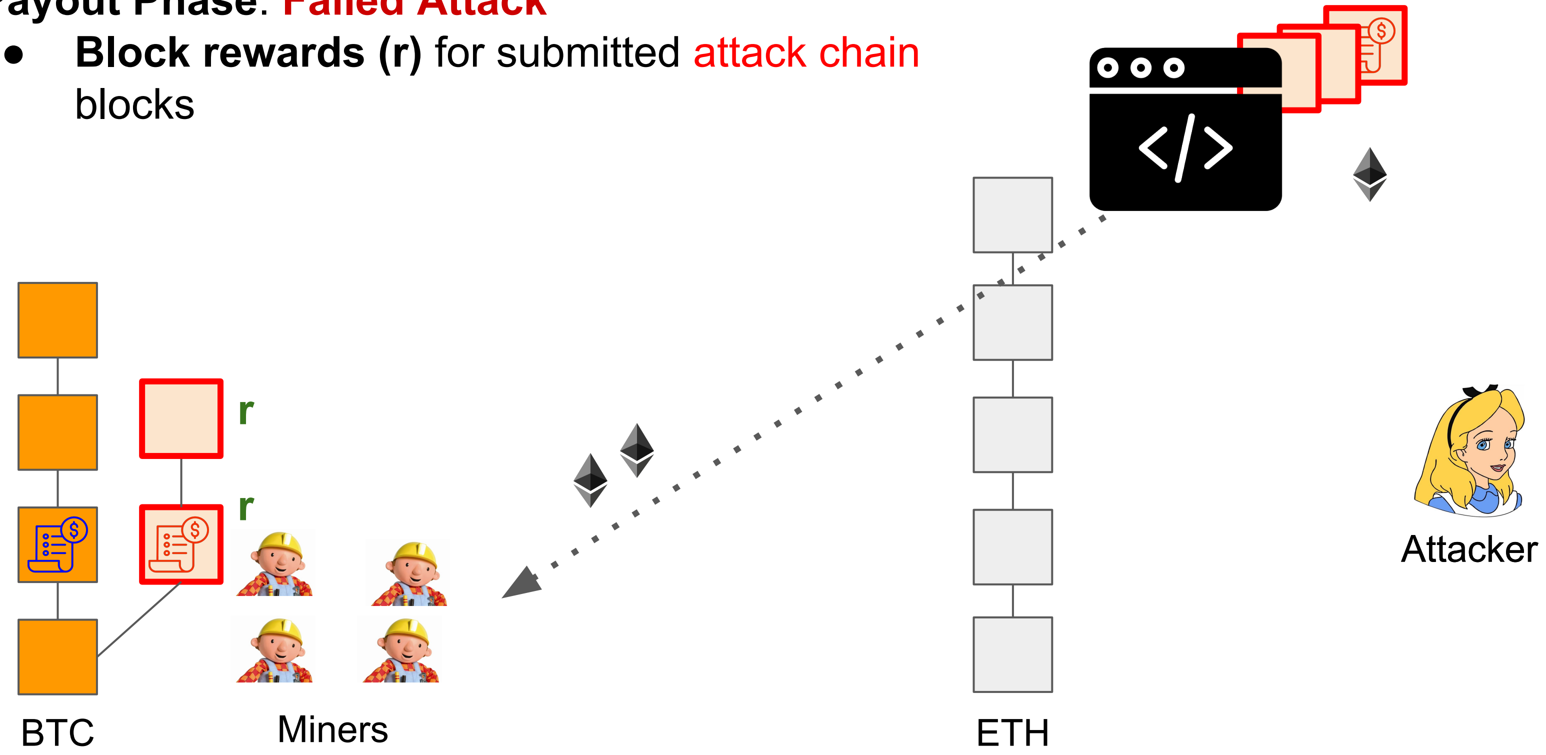




Pay-to-Win Attack (Deep Fork)

Payout Phase: **Failed Attack**

- **Block rewards (r)** for submitted attack chain blocks



Pay-to-Win Attack (Deep Fork)

Required funds at the start of attack:

$$N * (e + r) + k * r$$

N … attack duration
e … bribe
r … block reward
k … confirmation required by victim

Cost Evaluation

k = 6 (min. 6 main chain + 7 attack chain blocks to succeed)
r = 14 BTC *(~ block reward)*
e = 1 BTC (bribe - can be set way lower!)

Rational miners only (no victim hash rate)

- Failed attack ~ 98 BTC
- Successful attack ~ 91 BTC

Cost Evaluation

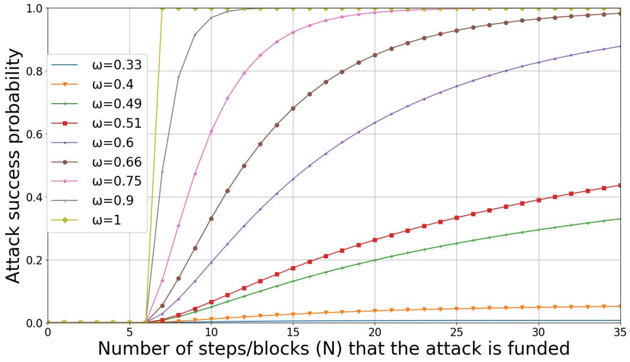
k = 6 (main chain must have 6 blocks before double spend succeeds)

r = 14 BTC *(~ block reward)*

e = 1 BTC (bribe - can be set way lower!)

Altruistic miners (victim has hash rate)

ω	whale costs	p2w costs c_{failed} (worst case lose)	% whale	p2w costs $c_{success}$ (worst case win)	% whale	p2w costs (expected win)
0.532	2.93e+23	7305	0.00	577	0.00	144
0.670	999.79	600	60.01	130	13.00	104
0.764	768.09	330	42.96	112	14.58	100
0.828	1265.14	240	18.97	106	8.38	99
0.887	1205.00	195	16.18	103	8.55	98
0.931	1806.67	165	9.13	101	5.59	98
0.968	2178.58	135	6.20	99	4.54	97
0.999	2598.64	120	4.62	98	3.77	97



See paper for more details!

Pros and Cons

+ **Difficult to detect** (cross-chain)
  → monitor all smart contract chains?
+ Miners have **no risk**
+ Only **small bribes** necessary
+ **No trust** required between attacker and miners

- Requires **smart contracts** on funding chain
- Funding chain must be able to **verify PoW** of target chain
- **Exchange rate** handling

Crowdfunding

- Use smart contract to coordinate multiple attacks in parallel
- Attackers lock in
  - e.g. double spend TX
  - compensation
- Attack costs are typically fixed!
  - Split among participants

Challenges: timing, sabotage via conflicting attacks, ...

See paper for more discussion!

Implications: Transaction Security

Typically, we assume a global ***k*** (Backbone model)

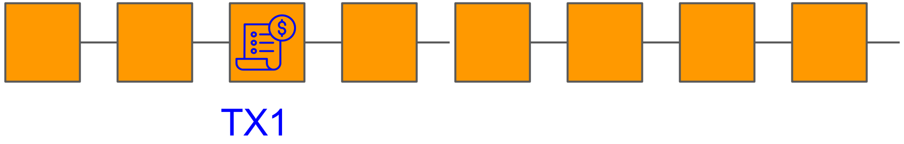
Sompolinksy et al. argue: “Take into account TX value!”

Recently:

Zindros argues: “Take into account value of entire block!”

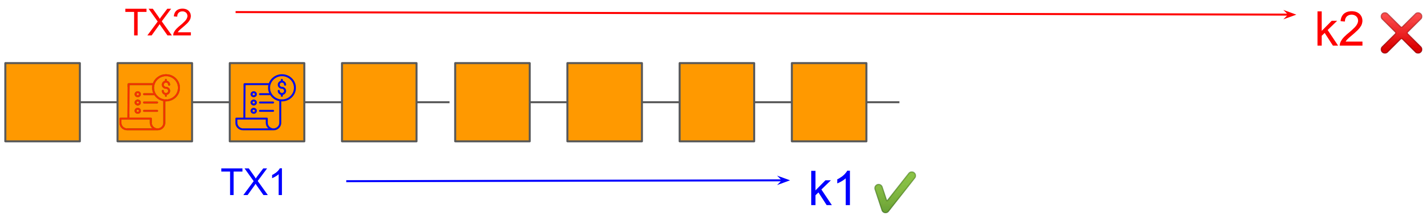
We conjecture: Even this is insufficient!

Implications: Transaction Security



Value of block of TX1 → set k1 (e.g. 6)

Implications: Transaction Security



Value of block of TX1 → set k1 (e.g. 6)

Problem: “juicy” TX2 in prev. block with high value being attacker

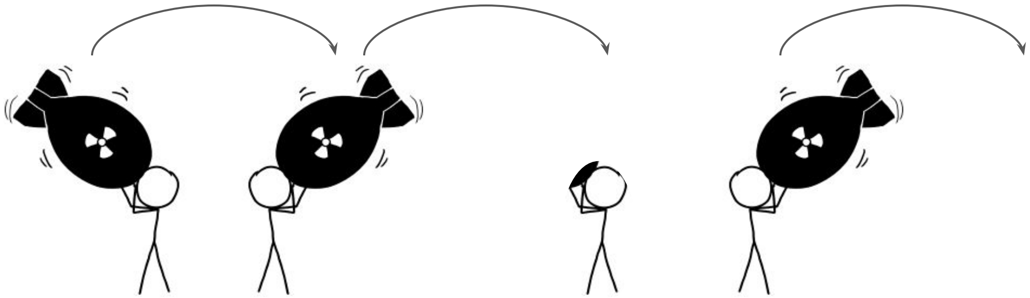
- k1 sufficient for TX1 alone… but what if the attack on TX2 **occurs anyway**?
- What if attacker of TX2 could also attack TX1 as “extra”?

→ In practice: **crowdfunded attacks**

What To Do? (Take With a Grain of Salt)

From theoretical perspective:

“HODLING” is risky!



Only “safety” measure:

As soon as you receive coins → spend & transfer risk!

This is theory! Less of a problem in practice.

SBA Research

TU WIEN TECHNISCHE UNIVERSITÄT WIEN Vienna University of Technology

Imperial College London

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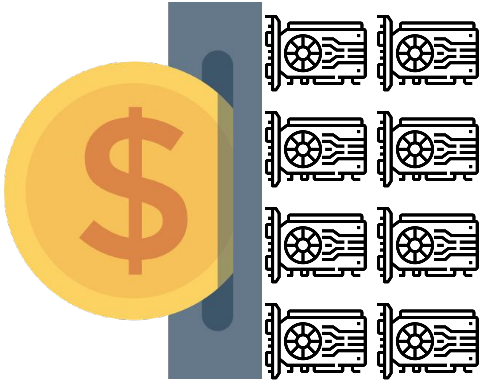
IC3 The Initiative For CryptoCurrencies & Contracts

Devcon 5 Research Meetup

11 October 2019, Osaka, Japan

Questions?



Pay-to-Win: Incentive Attacks on Proof-of-Work Cryptocurrencies

Aljosha Judmayer, Nicholas Stifter, Alexei Zamyatin, Itay Tsabary, Ittay Eyal, Peter Gazi, Sarah Meiklejohn, and Edgar Weippl