Towards a Game-Theoretic Security Analysis of Off-Chain Protocols

Computer Security Foundations Symposium 2023

July 10, Dubrovnik

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Informatics

for(syte)

(Dis-)Proving **Incentives and Punishment Mechanisms** in Off-Chain Protocols do what they should - using **Game Theory**

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Structure

- Incentive and Punishment Mechanisms
- Game-Theoretic Security Properties
- Modeling Protocols as Games
- Results

Example: Lightning Network

- Opening phase. A, B (couple) lock 5 coins each, claimed by redistribution $\rightarrow$ **Transaction on the blockchain**
- can redistribute their 10 coins multiple times
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- Update phase. E.g. B buys something for both (2 coins), A wants to give him her half.
  They agree on updating the redistribution state to 4 for Alice, 6 for Bob. $\to$ **off-chain**
- many more updates follow...

Example: Lightning Network

2 cases for closing phase

Consensus (honest).

- A, B still happy, want to close channel
- publish latest update **on the blockchain**
- receive fair part of money

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Dispute (honest).

- horrible break-up, closing required
- A wants to do better than last update
- A publishes old distribution state **on the blockchain**
- B can prove state is outdated
- B receives 10 coins, A 0 coins

Example: Lightning Network

punishment mechanism

honest behavior → fair split
dishonest behavior → lose all money

Honest Behavior

intended course of action in protocol

Is it always rational for cheated party to prove other published outdated state?

What is done already?

Cryptographic aspects of Blockchain protocols

- Universal Composability Framework:
- cryptography = ideal functionality

… but what about rationality?

Incentive / Punishment mechanisms

rely on **game-theoretic** arguments

e.g. Lightning’s closing

What do we verify?

– 3 types of users


honest


rational


Byzantine

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Byzantine

No one has a reason to deviate!

What do we verify?

- 3 types of users

honest | rational | Byzantine

No one has a reason to deviate!

done | honest = best | cannot harm honest

What do we verify?

- 1) Incentive-Compatibility 

  “no profit from deviation”

- 2) Byzantine-Fault Tolerance  

  - “even in presence of *Byzantine* users, *honest* ones not harmed”

Note: 1) + 2) enough

No assumption of honest/rational percentage

What do we verify *exactly*?

- 1) Incentive-Compatibility

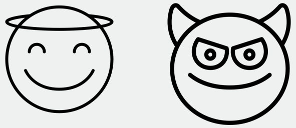
Collusion Resilience

$$\forall C, d_C. \quad \sum_{R \in C} u_R(h_C, h_{\neg C}) \geq \sum_{R \in C} u_R(d_C, h_{\neg C})$$

Practicality

always greedy choice

- 2) Byzantine-Fault Tolerance



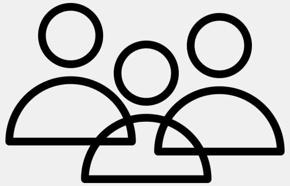
Weak Immunity

$$\forall r_{\neg H}. \quad u_H(h_H, r_{\neg H}) \geq 0$$

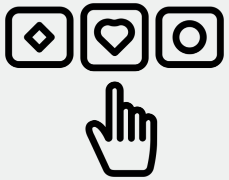
Introduction to Game Theory

Extensive Form Game

Finite set of players



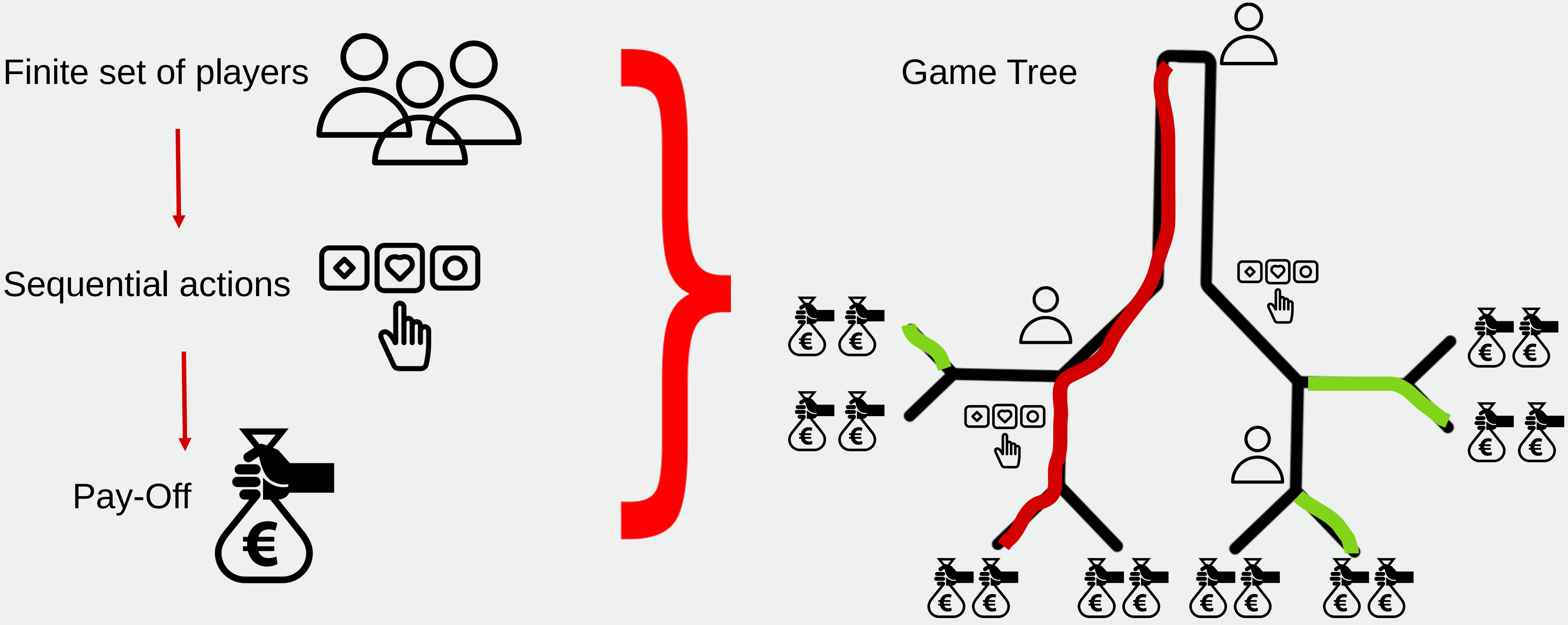
Sequential actions



Pay-Off

Introduction to Game Theory

Extensive Form Game



Modeling Lightning’s closing

A, B

A:

publish latest state (a,b)

publish old state (a+d, b-d)

sign closing tx (a,b), or (a+c,b-c)

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ignore (a+d, b-d)

prove it was old state (0, a+b-f)

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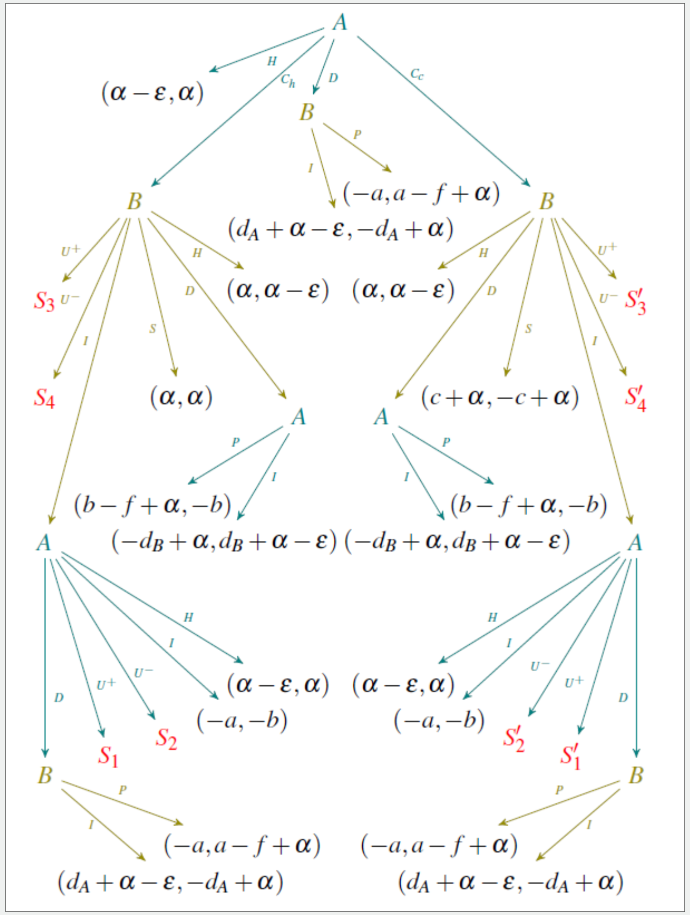
A: -a
B: a-f+alpha

symbolic, constraint, relative, infinitesimal, quantified

Full Model for Lightning’s Closing



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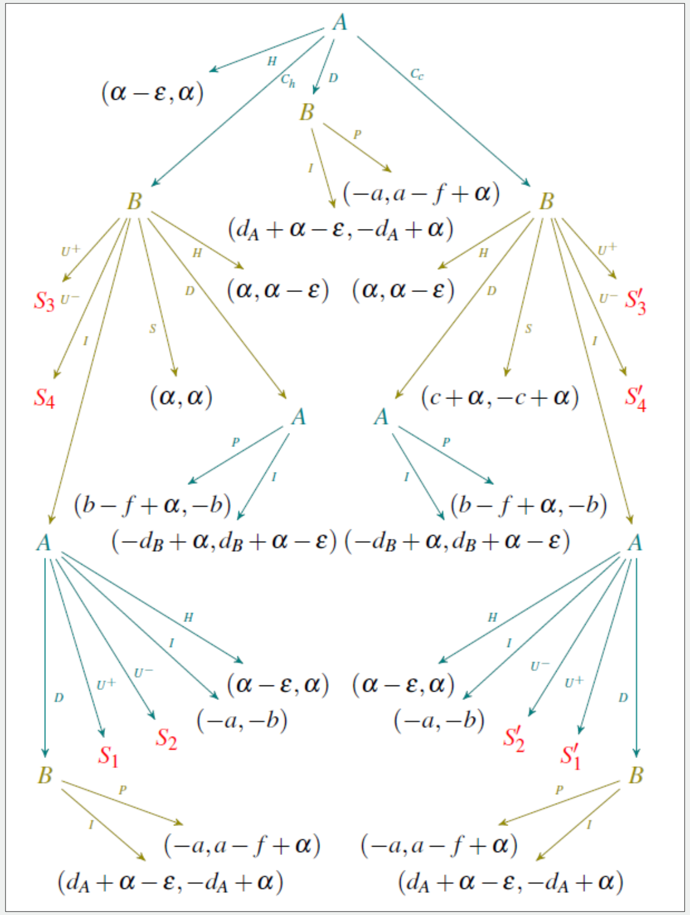

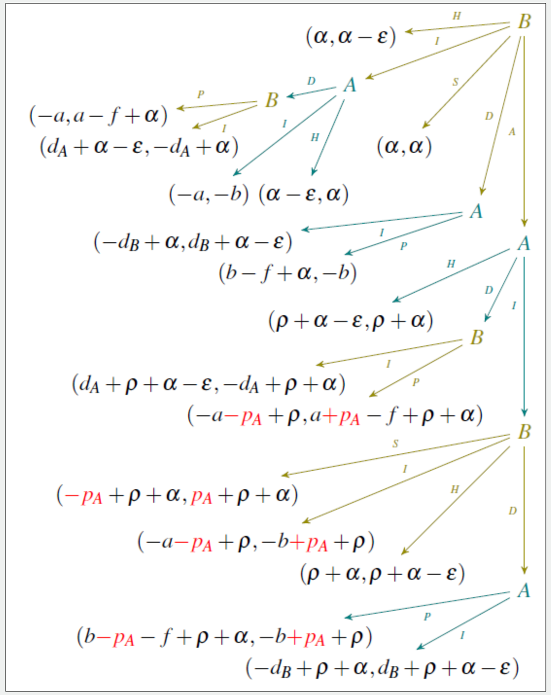

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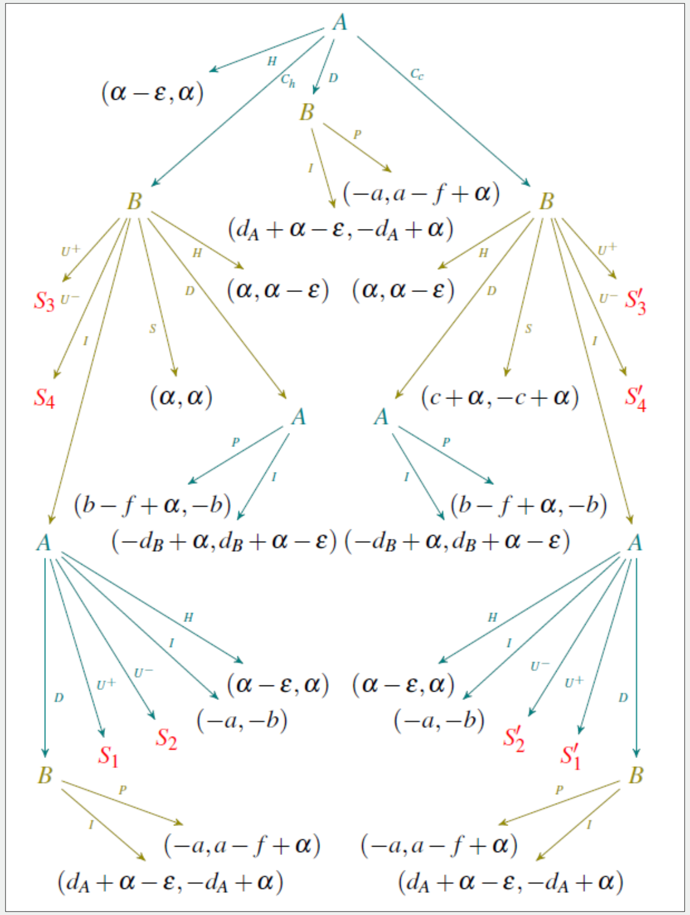

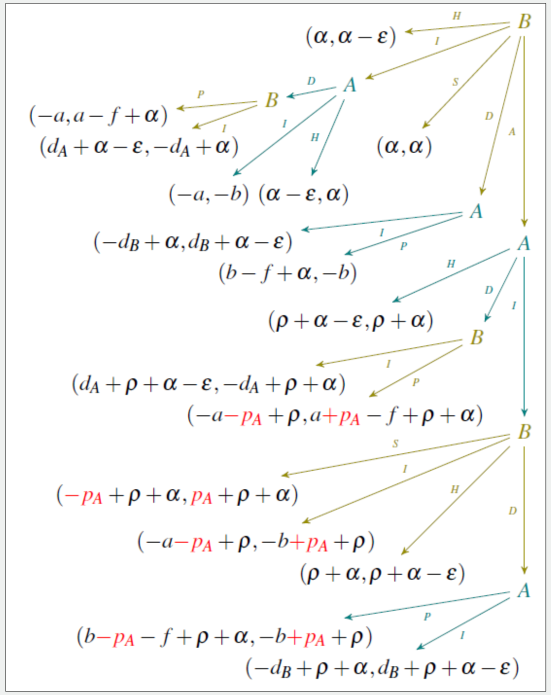

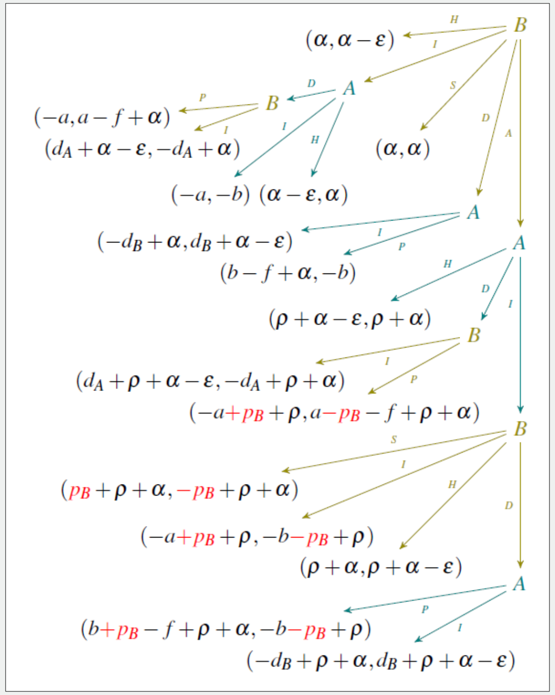

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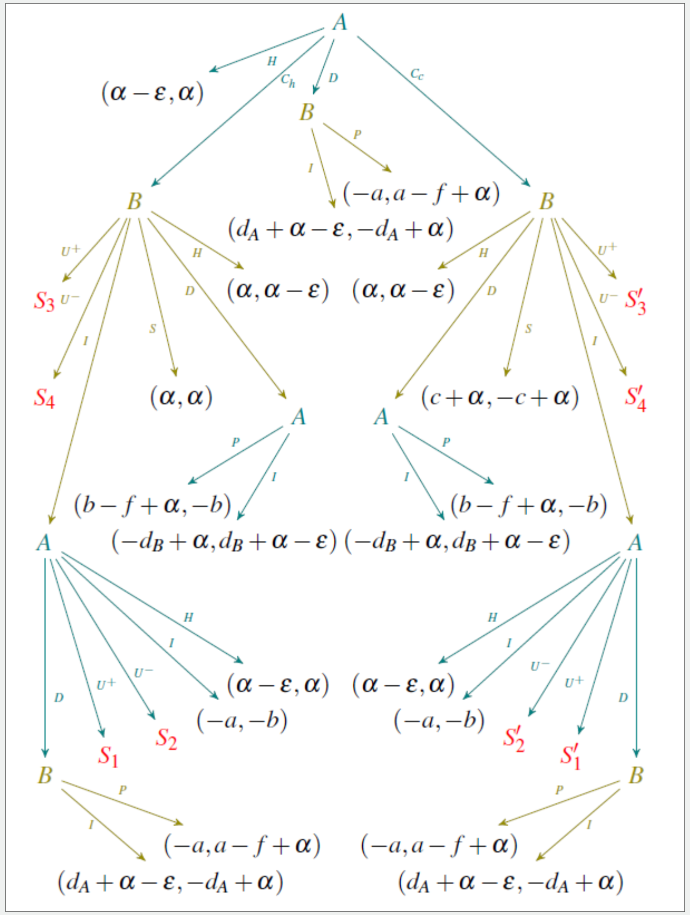

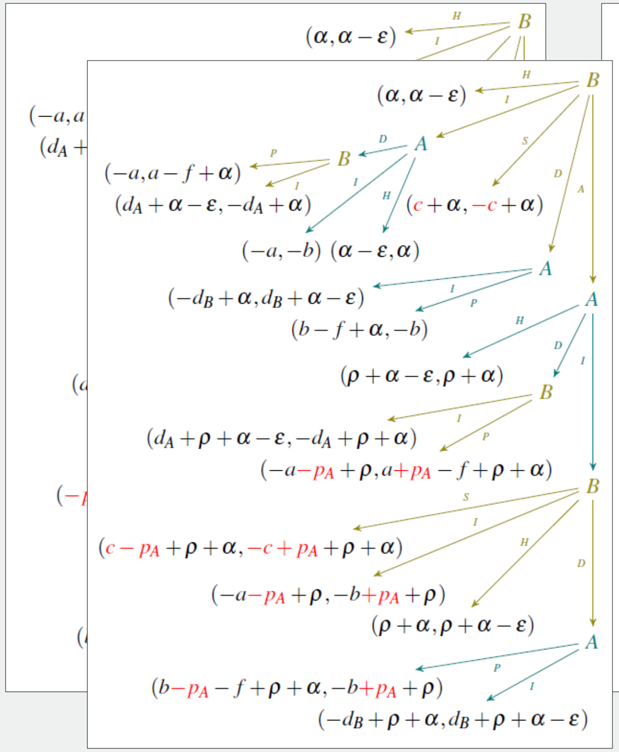

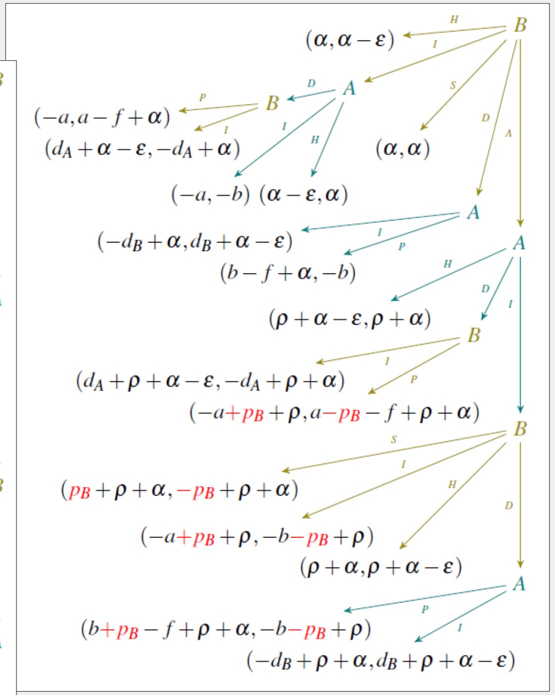

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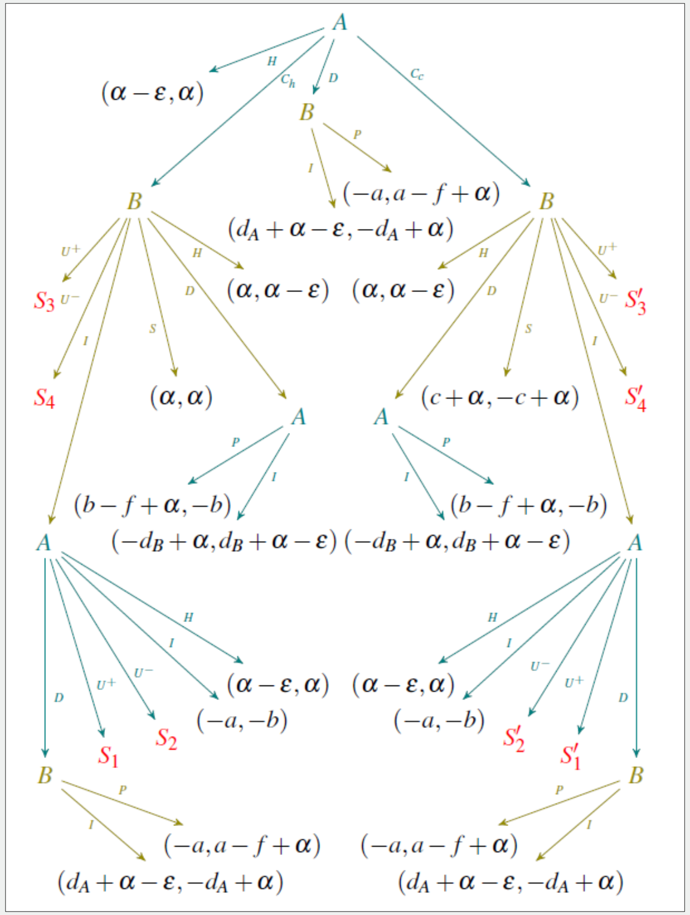

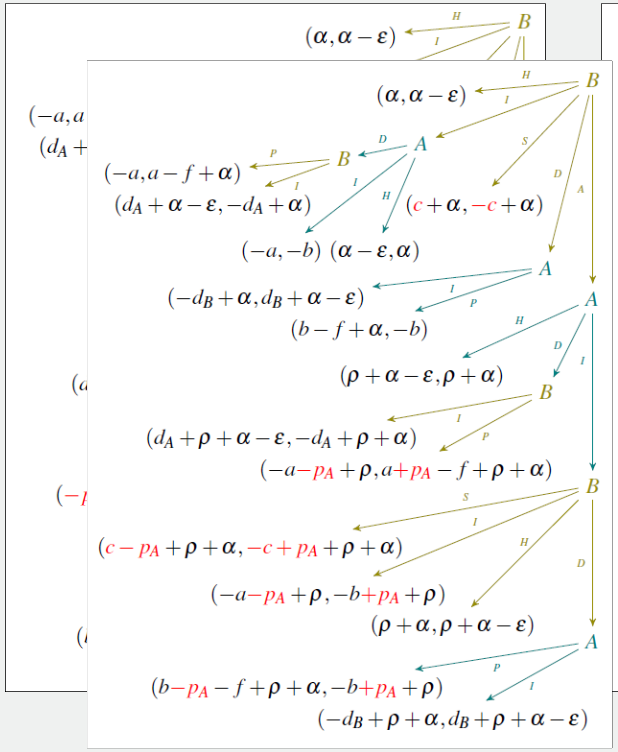

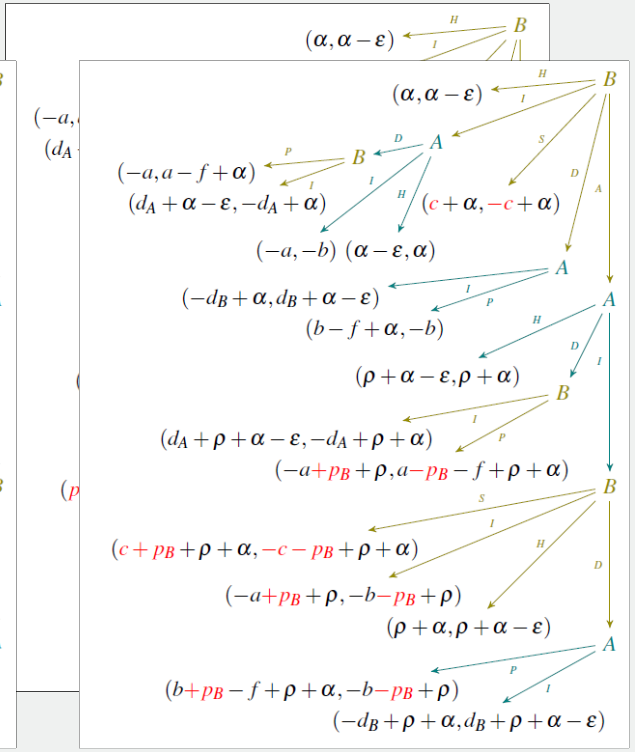

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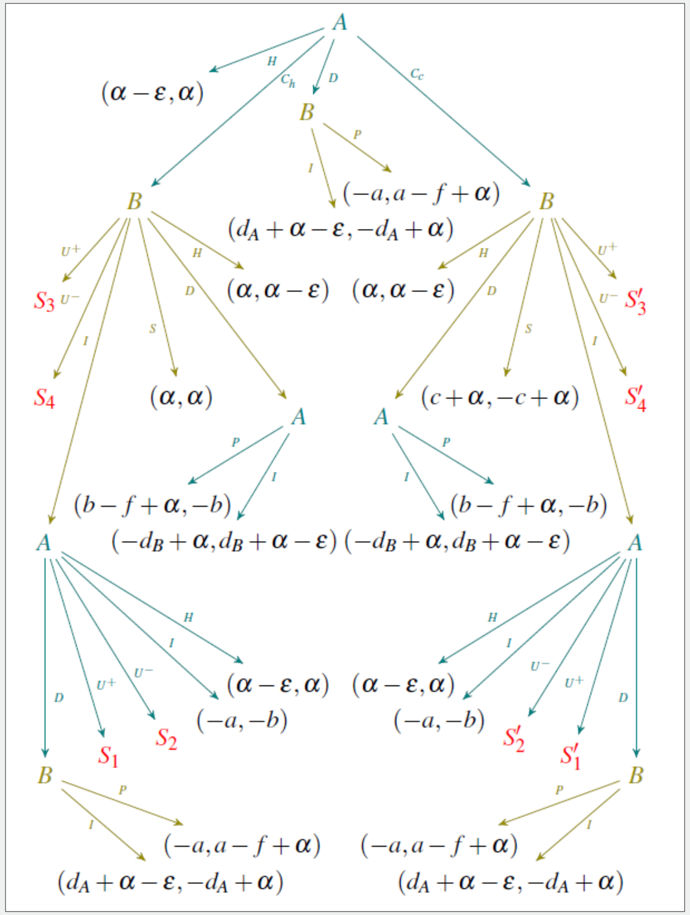

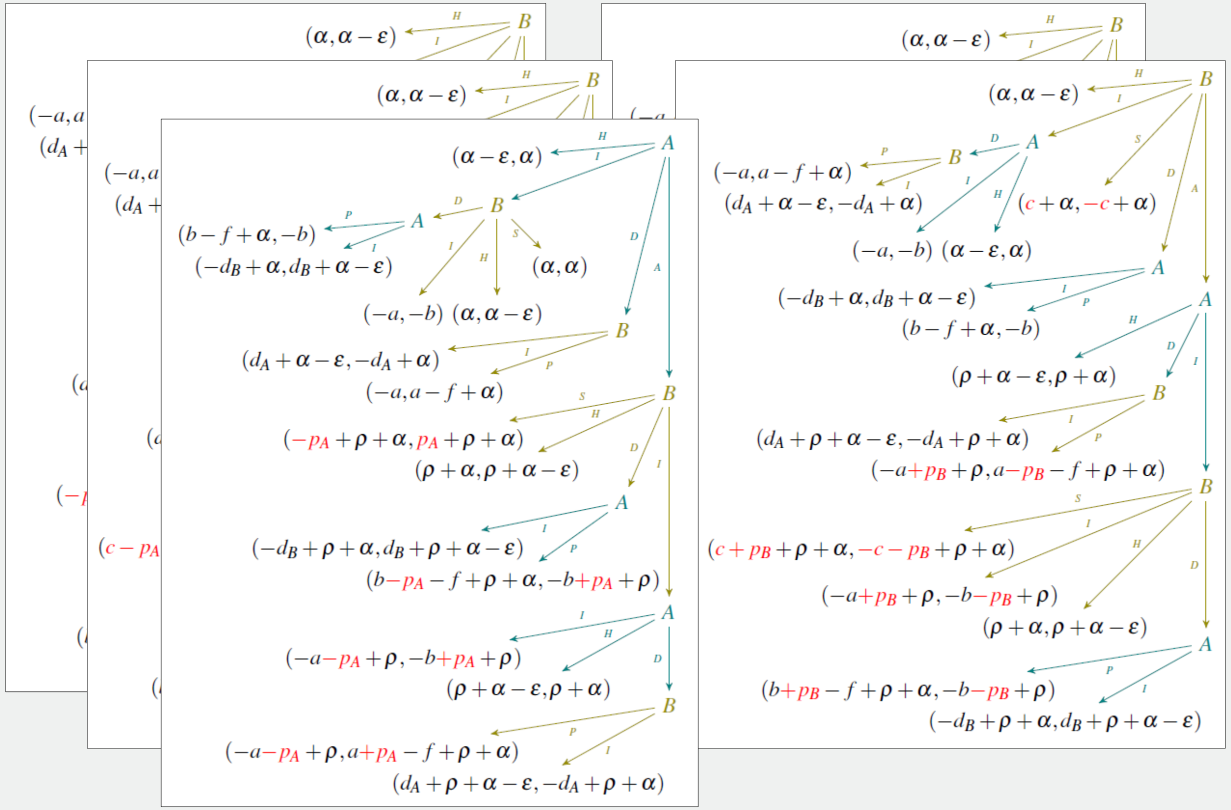

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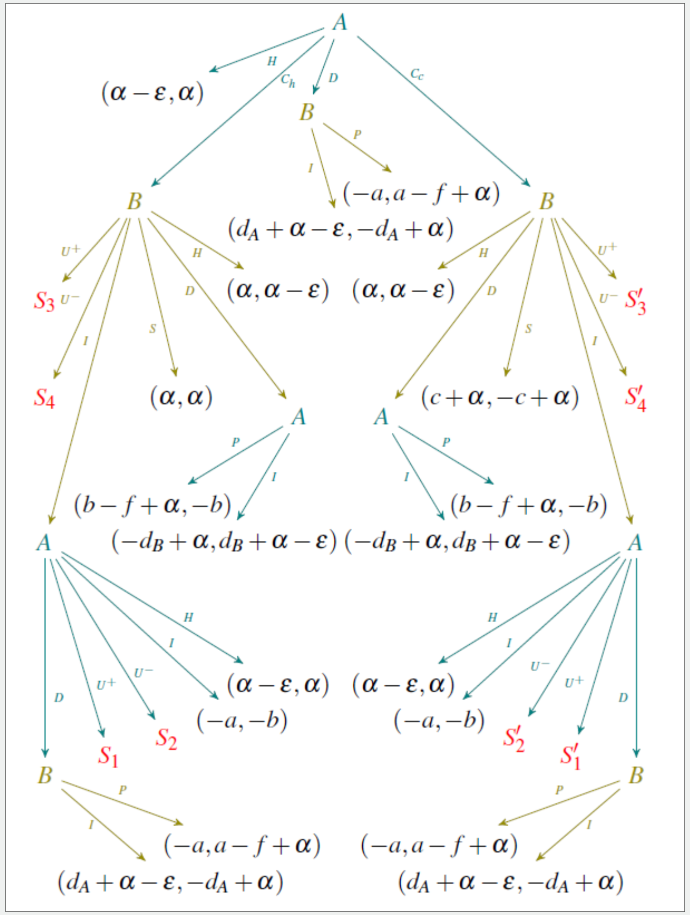

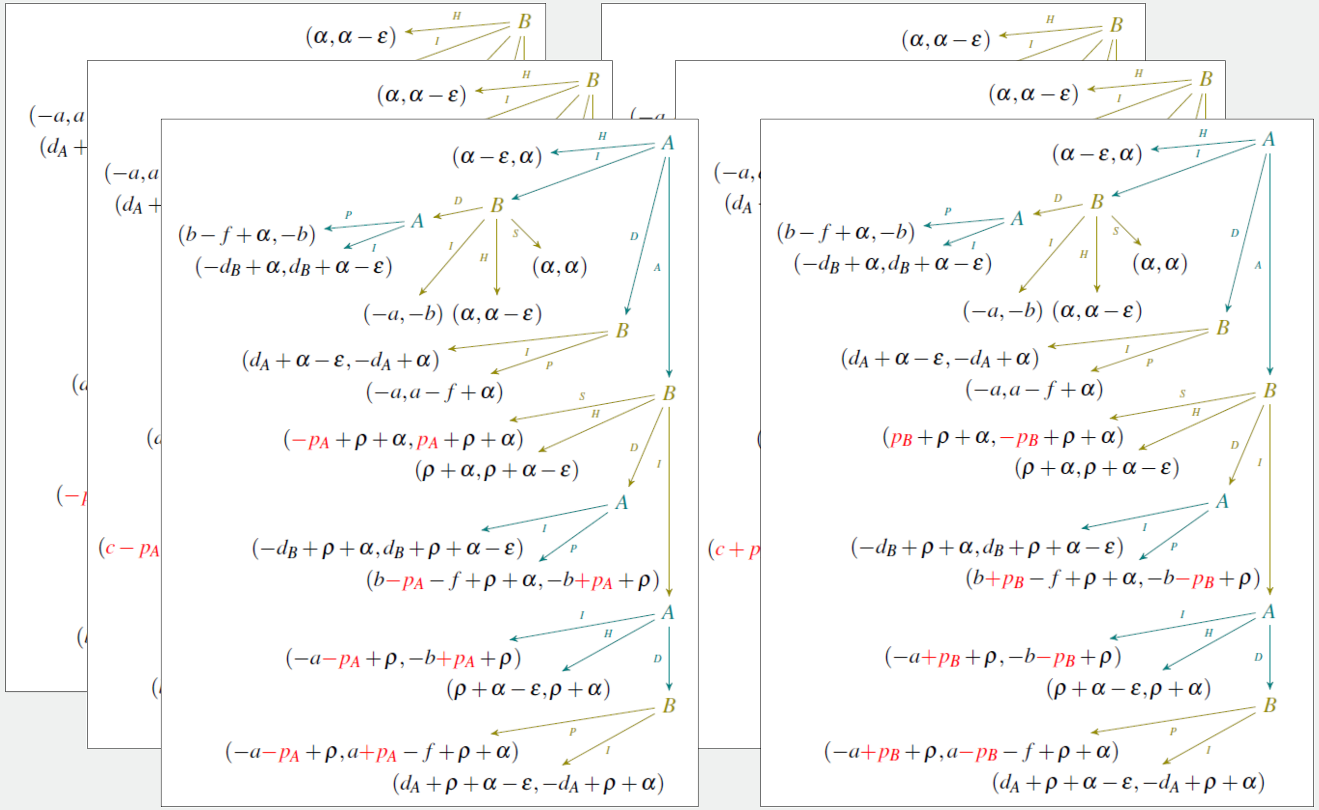

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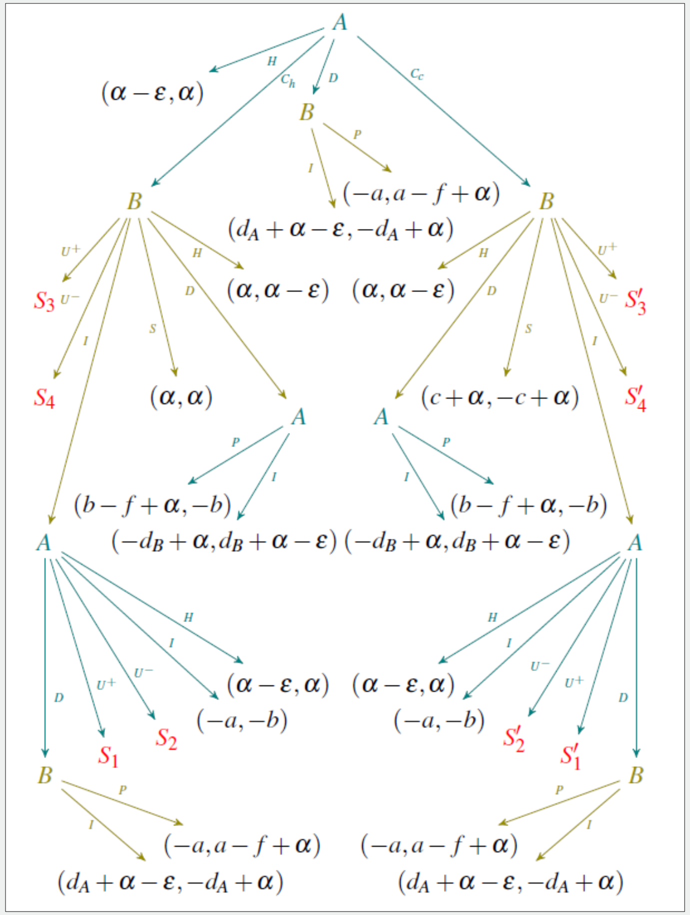

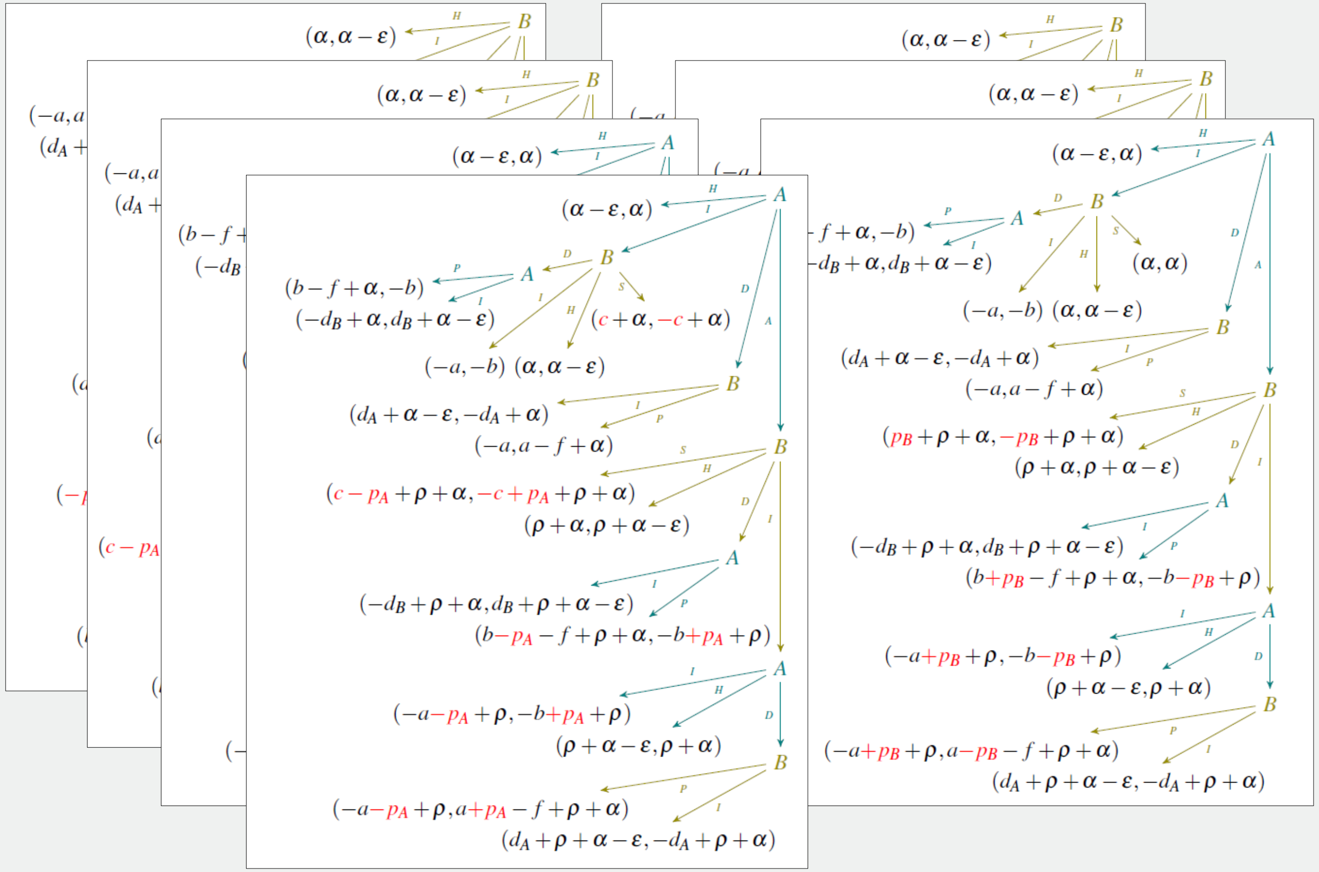

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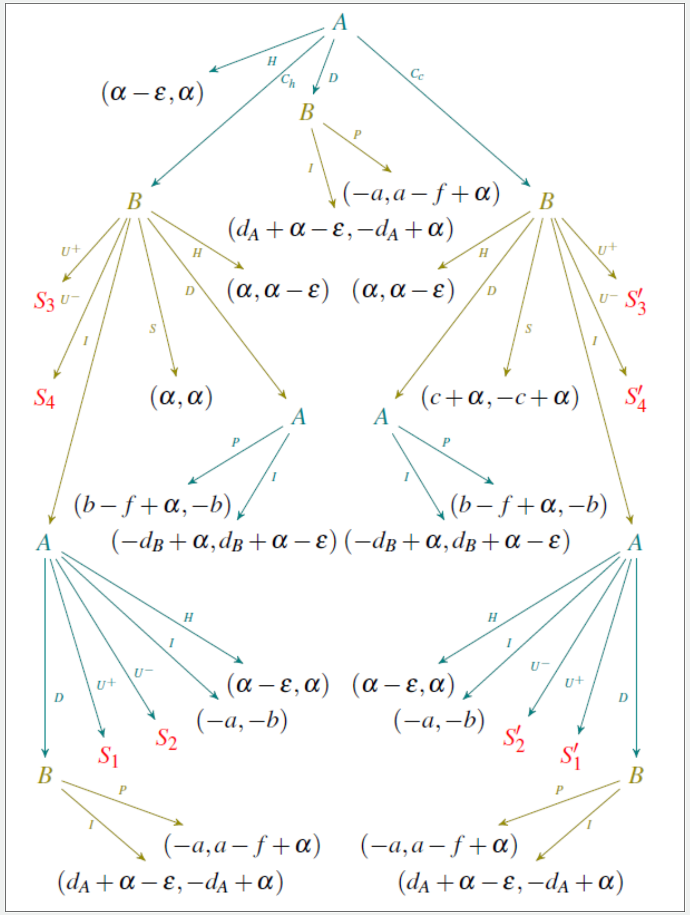

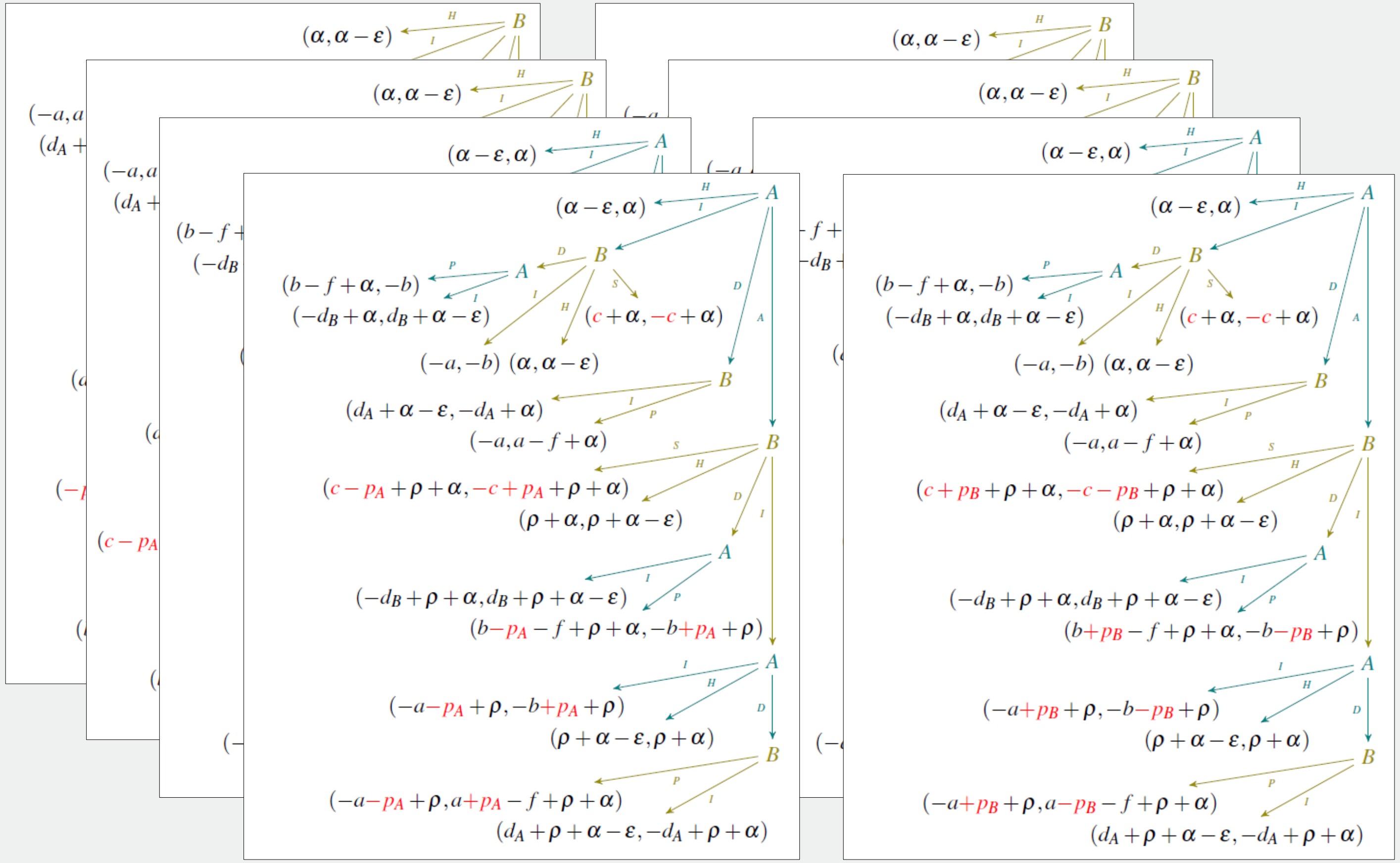

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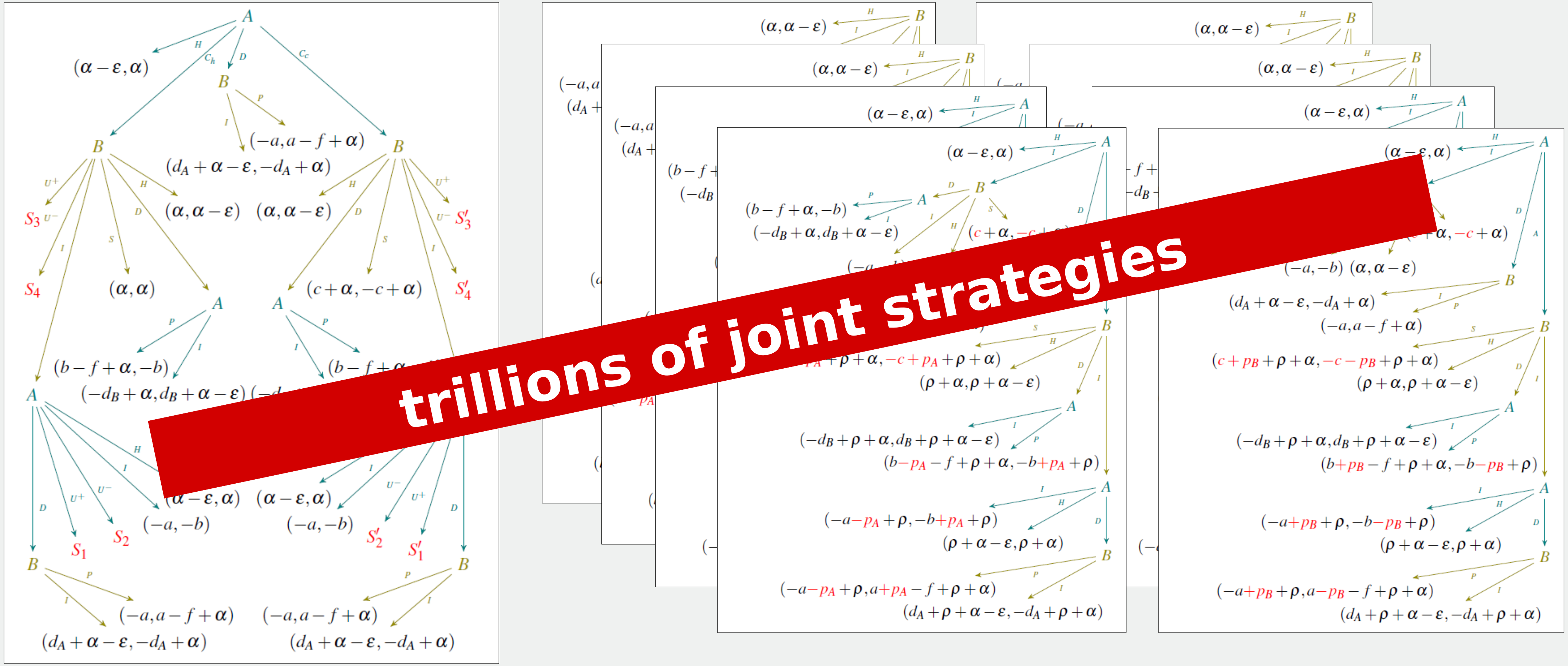
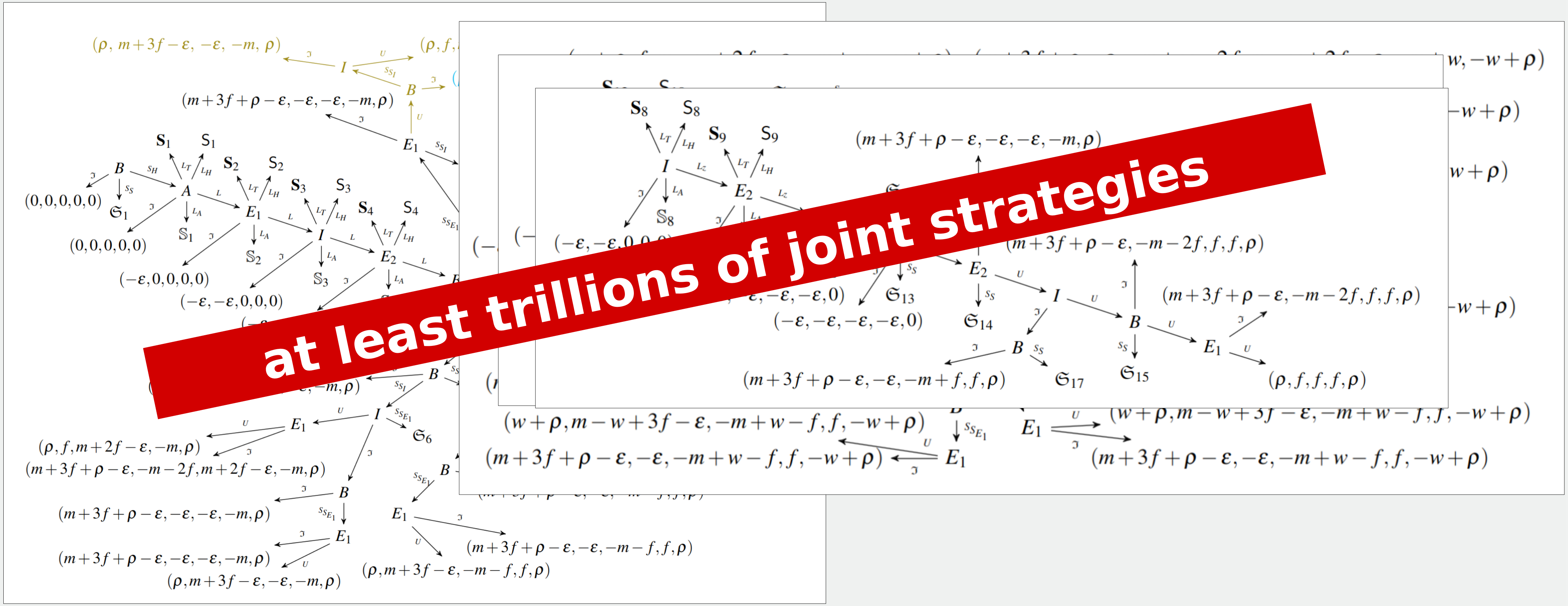
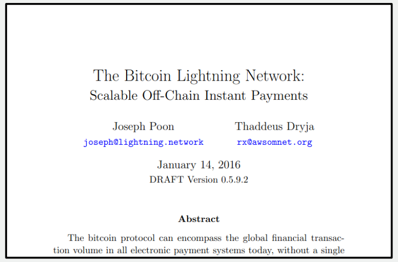


„Partial“ Model for Lightning’s Routing



How do we verify it?



The Bitcoin Lightning Network:
Scalable Off-Chain Instant Payments

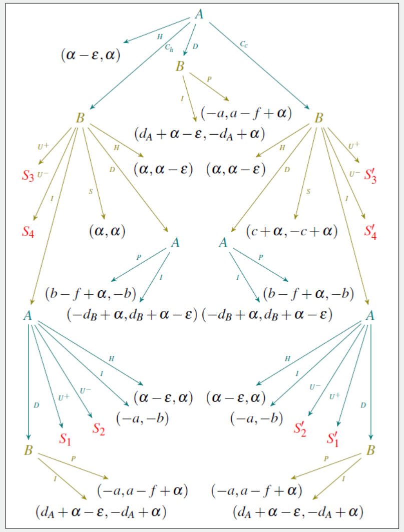
Joseph Poon joseph@lightning.network
Thaddeus Dryja rx@awsomnet.org

January 14, 2016
DRAFT Version 0.5.9.2

Abstract

The bitcoin protocol can encompass the global financial transaction volume in all electronic payment systems today, without a single

protocol + honest behavior



game + honest history

+

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security properties

authors

not satisfied

not secure

satisfied

secure

A Protocol is Secure, if...

...its intended behavior satisfies IC and BFT.

Protocol → Extensive Form Game

Intended Behavior → “honest” terminal history h*

A game + h* are **secure**, if…

...there are strategies extending h*, which are **weak immune**, **collusion resilient**, **practical**.

Security Results for Closing and Routing

No unknown attacks found.

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No unknown attacks found.

Closing ($a \rightarrow A$, $b \rightarrow B$):

Can honest participants be harmed? YES, if $a,b < f$

Is the honest behavior rational?
No, old state ($a+d \rightarrow A$, $b - d \rightarrow B$), where $a+d < f$

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Routing:

Can honest participants be harmed? YES

Is the honest behavior rational? NO

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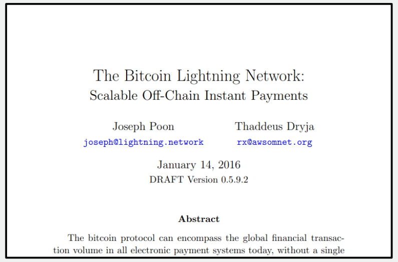
Take-Away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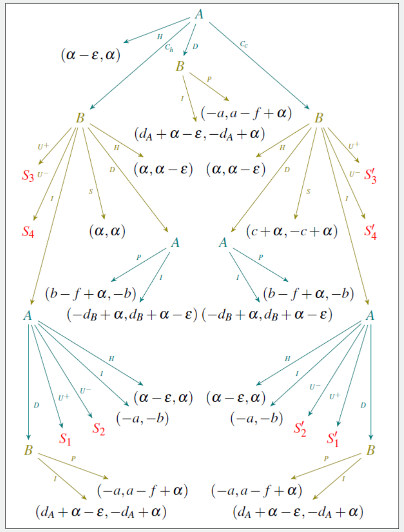

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