

A Language for Quantifying Quantum Network Behavior

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Quantum networks

Quantum networks are networks connecting quantum capable devices

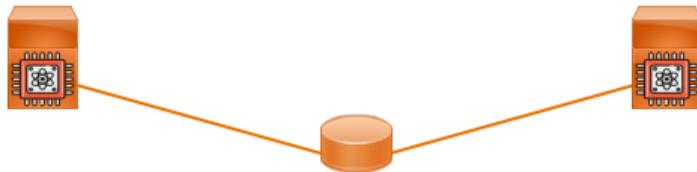
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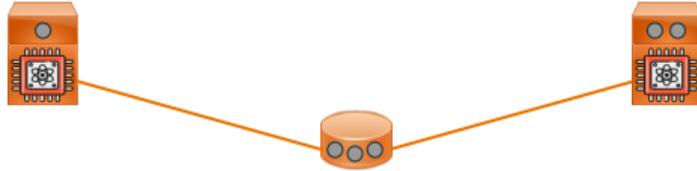
Quantum networks

Quantum networks are networks connecting quantum capable devices



Quantum networks

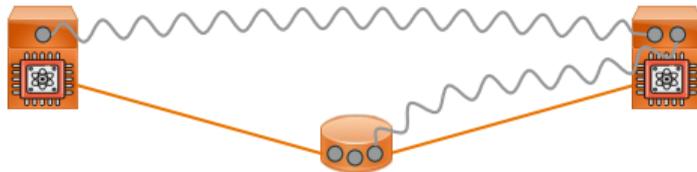
Quantum networks are networks connecting quantum capable devices



- **Communication qubits** designated to establish *connections* between devices

Quantum networks

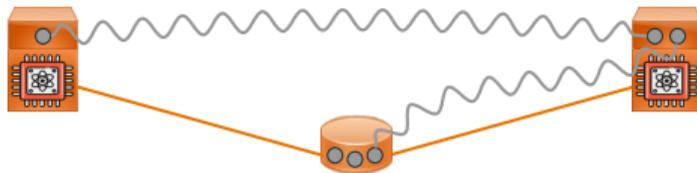
Quantum networks are networks connecting quantum capable devices



- **Communication qubits** designated to establish *connections* between devices
- Distributed entanglement: tightly *correlated* communication qubits

Quantum networks

Quantum networks are networks connecting quantum capable devices



- **Communication qubits** designated to establish *connections* between devices
- Distributed entanglement: tightly *correlated* communication qubits

Benefits: **scaling of quantum computation** and **secure communication**



- teleportation
- entanglement based QKD

¹[2025 IBM Quantum Innovation Roadmap]

Quantum networks are becoming a reality

Open Access Article

DOI:10.1145/3524455

A deep dive into the quantum Internet's potential to transform and disrupt.

BY LASZLO GYONGYOSI AND SANDOR IMRE

Advances in the Quantum Internet

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Creation of memory-memory entanglement in a metropolitan quantum network

Jian-Long Liu, Xi-Yu Luo, Yong Yu, Chao-Yang Wang, Bin Wang, Yi Hu, Jun Li, Ming-Yang Zhi, Yao, Zi Yan, Da-Teng, Jin-Wei Jiang, Xiao-Bing Liu, Xu-Ping Xie, Jun Zhang, Qing-He Mao, Qiang Zhang, Xiao-Hui Bao & Jian-Wei Pan

Nature 629, 579–585 (2024) | Cite this article

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The quantum Internet uses the fundamental concepts of quantum mechanics for networking (see Sidebars 1–7 in the online Supplementary Information at <https://doi.org/10.1145/3524455>). The main attributes of the quantum Internet are advanced quantum phenomena and protocols (such as quantum superposition and quantum entanglement, quantum teleportation, and advanced quantum coding methods), unconditional security

ScienceAdvances

RESEARCH ARTICLE | PHYSICS

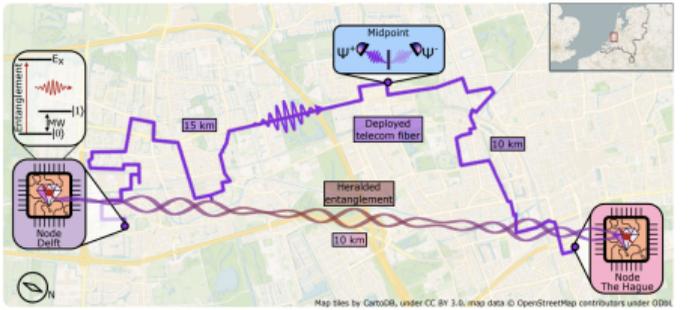
Metropolitan-scale heralded entanglement of solid-state qubits

ARIAN J. STOLK, XIAN L. VAN DER ENDEN, MARIE-CHRISTINE SLATER, INGMAR TE BAA-GERDCKY, PETER BOTMA, JORIS VAN RANTWILK, J. J. BENJAMIN REMOND, RONALD A. J. HAGEN, RIDDLE W. HERST, I. J. AND RONALD HANSON

13 authors | Authors Info & Affiliations

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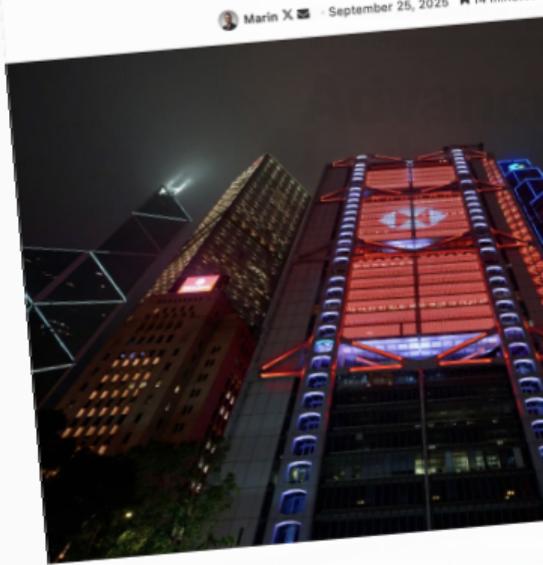
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practical quantum networks for long-distance quantum entanglement between quantum memory nodes... Here we demonstrate a two-node quantum network based on silicon-vacancy (SiV) centres in nanophotonic waveguides with a telecommunication fibre network. Remote entangled interactions between the electron spin qubits of heralded spin-photon entangling gate operations with the entanglement of separated nodes. Long-lived nuclear spin qubits enable entanglement storage and integrated error detection. The quantum frequency conversion of photonic communication frequencies (1.55–1.56 μm) to

Quantum networks are becoming a reality

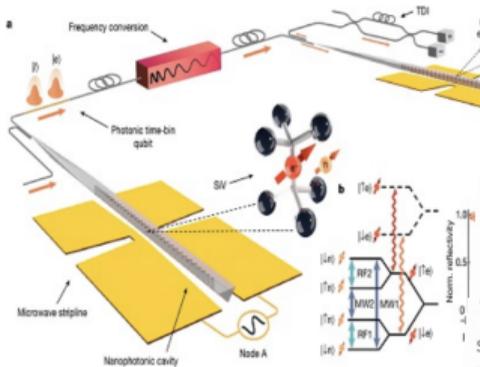
HSBC and IBM's Quantum-Enabled Bond Trading Breakthrough

Marin X · September 25, 2025 · 14 minutes read



quantum Internet uses the fundamental concepts of quantum physics for networking (see Sidebar in the online Supplementary Information at <https://doi.org/10.1038/s41585-024-0455-5>). The main attributes of quantum Internet are advanced phenomena and protocols

AT
To: ACM TechNews <technews-edit>
 Buckley Anita



Quantum Internet Draws Nearer

Harvard University researchers assembled a quantum network spanning 35 kilometers across Boston, MA. The network is comprised of two nodes separated by a loop of optical fiber, each featuring a type of diamond with an atom-sized hole. Meanwhile, researchers at the

Cisco shows quantum networking opens new lab

By Stephen Nellis

May 6, 2025 6:52 PM GMT+2 · Updated May 6, 2025



The Cisco logo is displayed, during the GSMA's 2023 Mobile World Congress (MWC) in Barcelona, Spain March 1, 2023. REUTERS/Doce/File photo [Purchase Licensing Rights](#)

SAN FRANCISCO, May 6 (Reuters) - Cisco Systems on Tuesday showed a prototype chip for networking quantum computers together and said it is opening a new lab in Santa Monica, California, to further pursue quantum computing.

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entanglement storage and integrated error detection
quantum frequency conversion of photonic
communication frequencies (1.350-1.550 nm)

Bell pair: a pair of entangled qubits

- Fundamental *resource* in quantum networks
- *Bell pair* is a pair of entangled qubits:
 $R \sim B$ distributed between nodes R and B
- Carry no control information



Image by Andrij Borys Associates, using Shutterstock
Quantum Wheel in ArtScience Museum Singapore

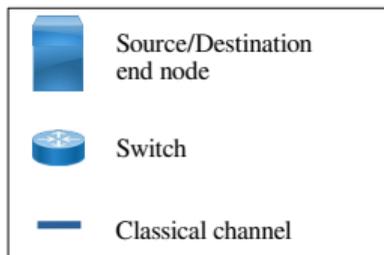
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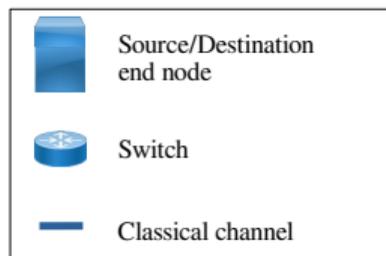


Image by Andrij Borys Associates, using Shutterstock
Quantum Wheel in ArtScience Museum Singapore

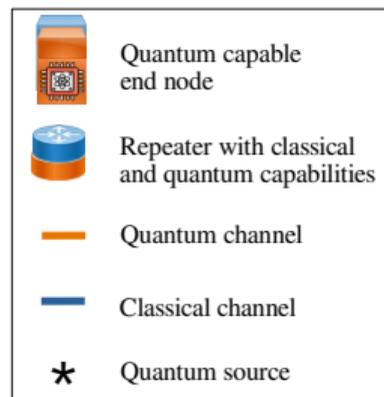
Classical network



Classical network



Quantum network^{1,2}



¹[Kozłowski and Wehner: NANOCOM 2019],

²[Quantum Internet Research Group: RFC 9340 2023]

Classical network



Quantum network



Forwarding packets



$\{S\}$

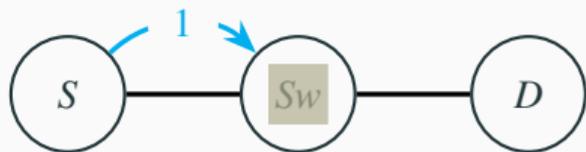
- Node
- Physical channel
- Packet

Distributing Bell pairs



- Node
- Physical channel
- Bell pair

Forwarding packets



$\{S\} \longrightarrow \{Sw\}$

- Node
- Physical channel
- Packet

Distributing Bell pairs



- Node
- Physical channel
- Bell pair

Forwarding packets



$\{S\} \longrightarrow \{Sw\} \longrightarrow \{D\}$

- Node
- Physical channel
- Packet

Distributing Bell pairs



- Node
- Physical channel
- Bell pair

Forwarding packets



$\{S\} \longrightarrow \{Sw\} \longrightarrow \{D\}$

- Node
- Physical channel
- Packet

Distributing Bell pairs



- Node
- Physical channel
- Bell pair

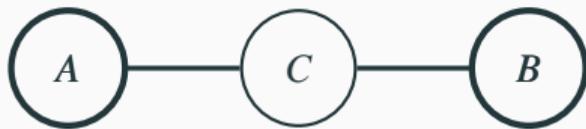
Forwarding packets



$\{S\} \longrightarrow \{Sw\} \longrightarrow \{D\}$

- Node
- Physical channel
- Packet

Distributing Bell pairs



- Node
- Physical channel
- Bell pair

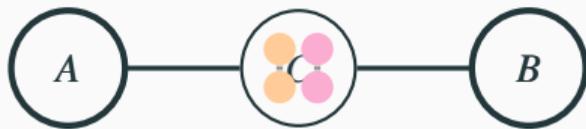
Forwarding packets



$\{S\} \longrightarrow \{Sw\} \longrightarrow \{D\}$

- Node
- Physical channel
- Packet

Distributing Bell pairs



$\{C \sim C, C \sim C\}$

- Node
- Physical channel
- ~● Bell pair

Forwarding packets



$\{S\} \longrightarrow \{Sw\} \longrightarrow \{D\}$

- Node
- Physical channel
- Packet

Distributing Bell pairs



$\{C \sim C, C \sim C\}$

- Node
- Physical channel
- Bell pair

Forwarding packets



$\{S\} \longrightarrow \{Sw\} \longrightarrow \{D\}$

- Node
- Physical channel
- Packet

Distributing Bell pairs



$\{C \sim C, C \sim C\} \rightarrow \{A \sim C, B \sim C\}$

- Node
- Physical channel
- Bell pair

Forwarding packets



$\{S\} \longrightarrow \{Sw\} \longrightarrow \{D\}$

- Node
- Physical channel
- Packet

Distributing Bell pairs



$\{\{C \sim C, C \sim C\}\} \rightarrow \{\{A \sim C, B \sim C\}\}$

- Node
- Physical channel
- Bell pair

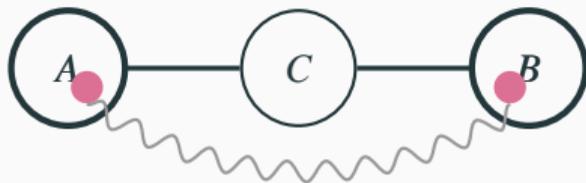
Forwarding packets



$\{S\} \longrightarrow \{Sw\} \longrightarrow \{D\}$

- Node
- Physical channel
- Packet

Distributing Bell pairs



$\{C \sim C, C \sim C\} \rightarrow \{A \sim C, B \sim C\} \longrightarrow \{A \sim B\}$

- Node
- Physical channel
- ~● Bell pair

PROBLEM

How to make sure that quantum networks behave as intended?

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SOLUTION

Provide formalism as foundation to answer these types of questions

PROBLEM

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- Are two protocols equivalent?
- Can protocols run in parallel without interfering with each other?

SOLUTION

BellKAT: An Algebraic Language for Specifying Quantum Networks. *PLDI'24*

Quantitative analysis

PROBLEM

How to reason about quantitative properties of quantum networks?

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- What is the expected number of protocol iterations required to generate $A \sim B$?
- How can we improve the rate at which a protocol generates Bell pairs?

SOLUTION

Provide formalism as foundation to answer such *quantitative* questions

A language for quantifying quantum network protocols – PBKAT

A language for quantifying quantum network protocols – **Probabilistic** BellKAT

A language for quantifying quantum network protocols – Probabilistic **BeII**KAT

A language for quantifying quantum network protocols – Probabilistic Bell**KAT**

A language for quantifying quantum network protocols – **PBKAT**

- probabilistic behavior (expressing failures in quantitative terms)

A language for quantifying quantum network protocols – **PBKAT**

- probabilistic behavior (expressing failures in quantitative terms)
- nondeterministic behavior (arising from concurrency / resource contention)

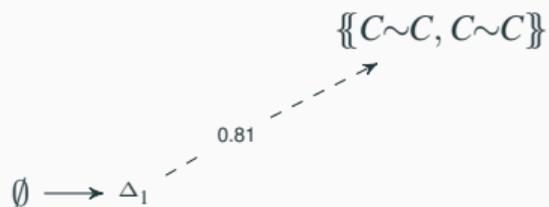
PBKAT protocol

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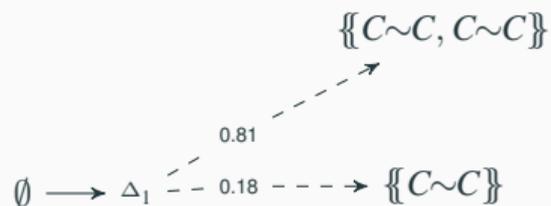
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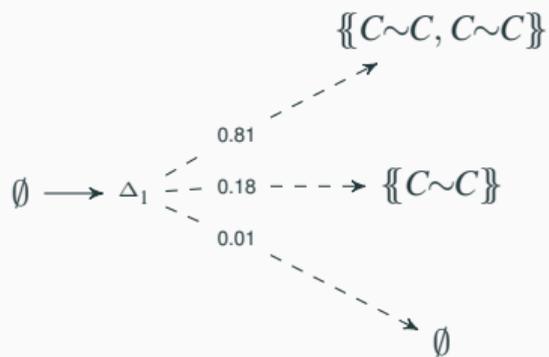
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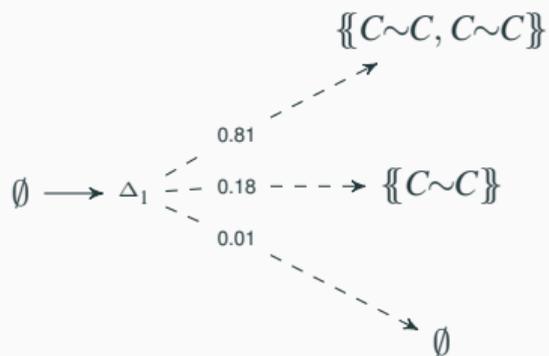
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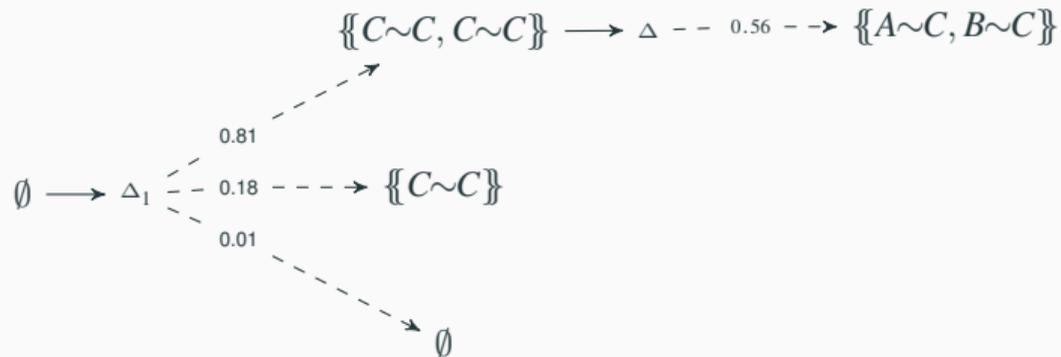
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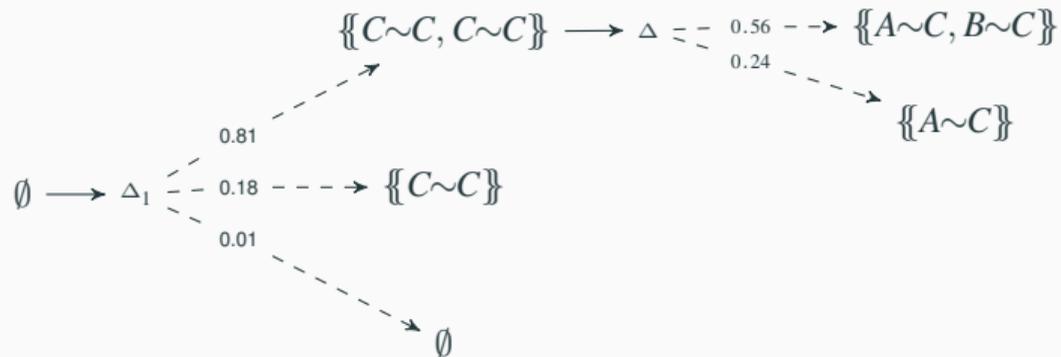
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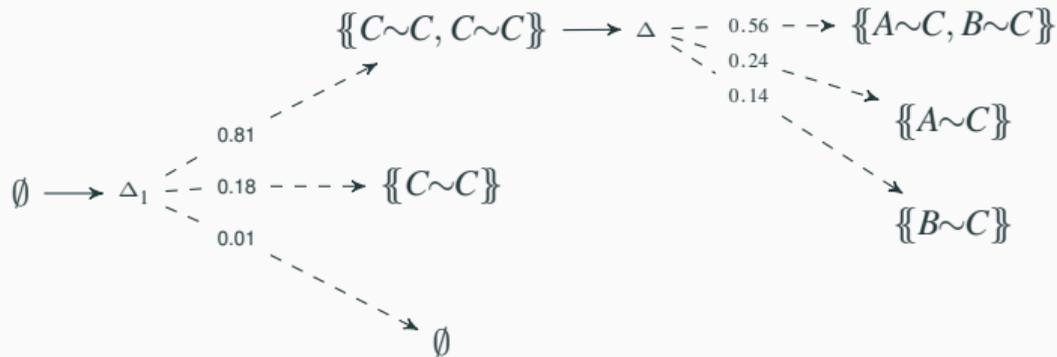
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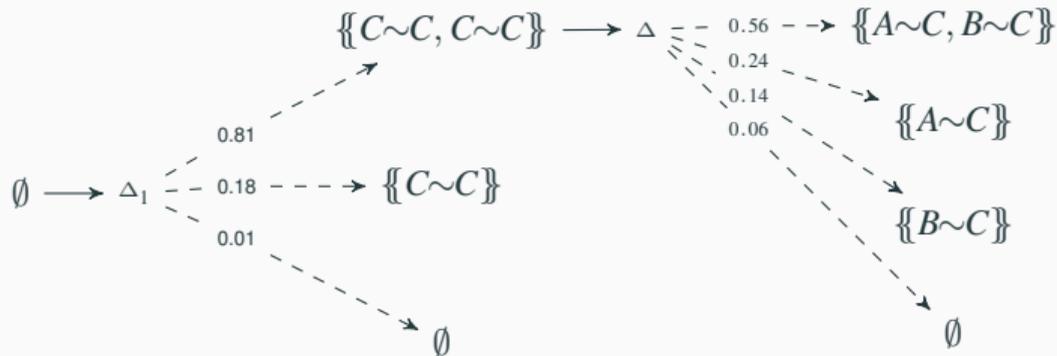
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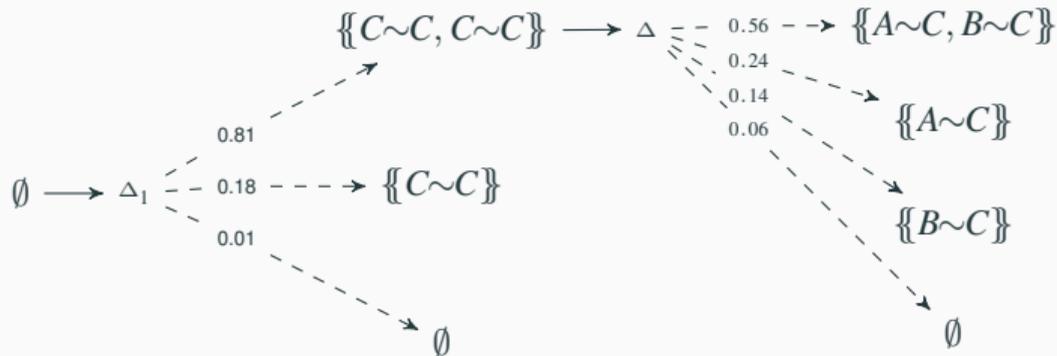
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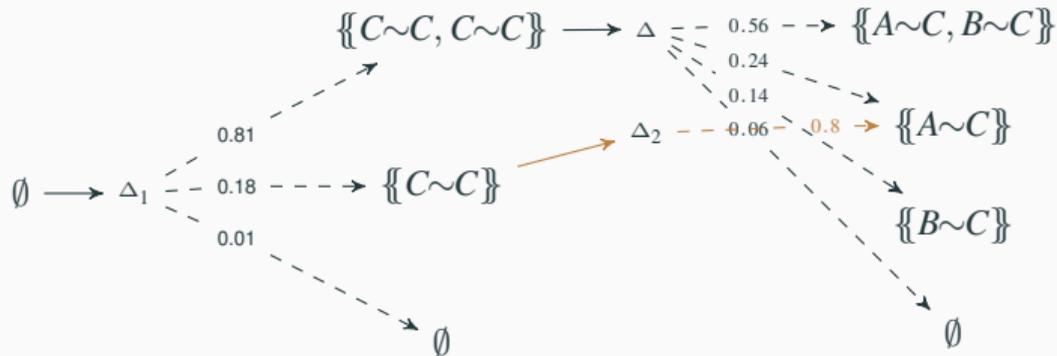
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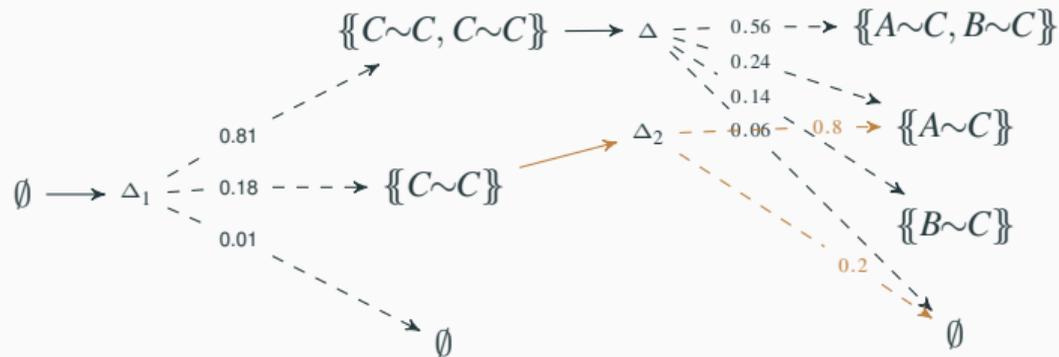
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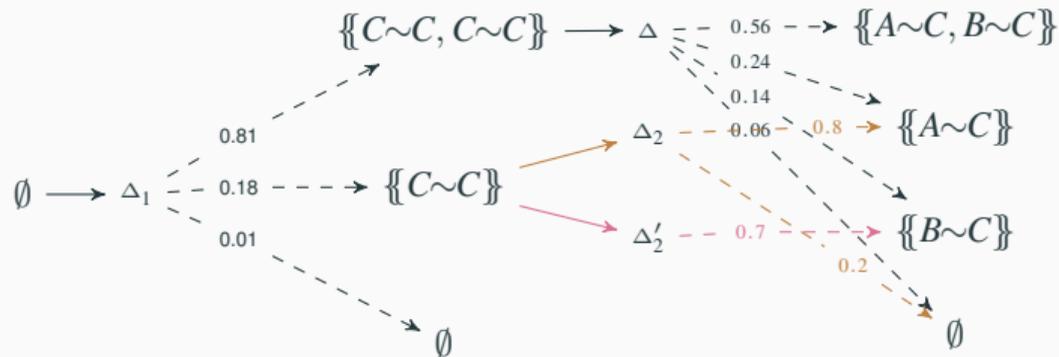
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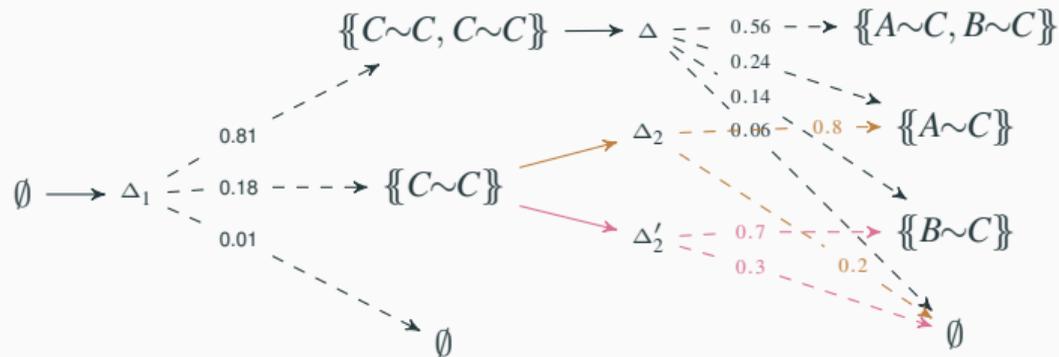
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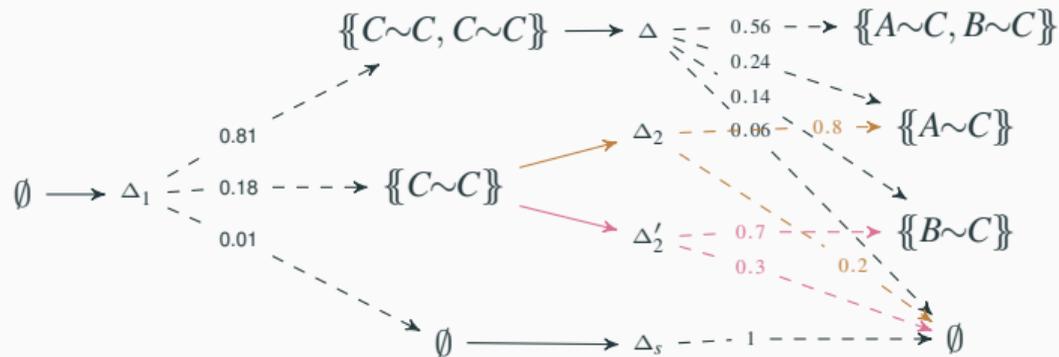
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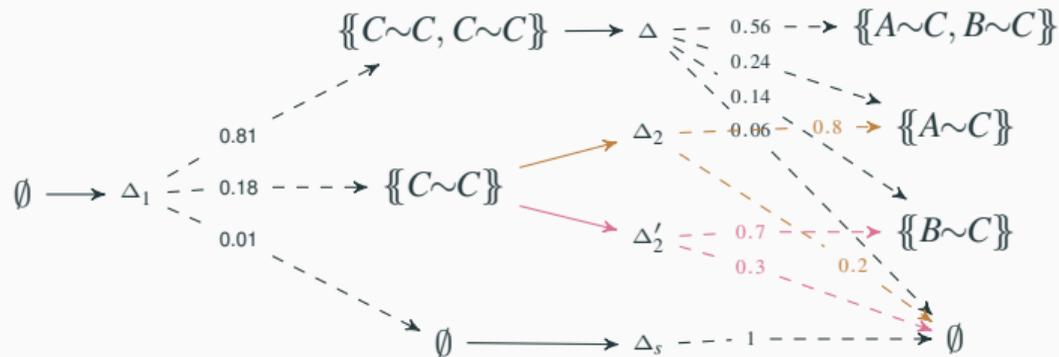
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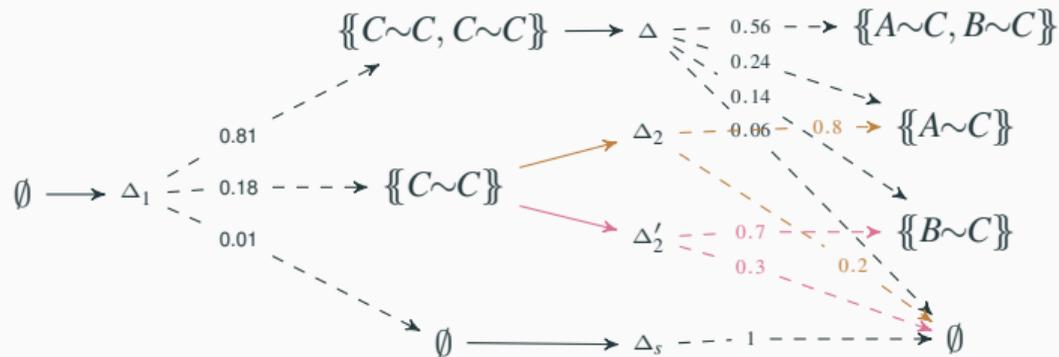
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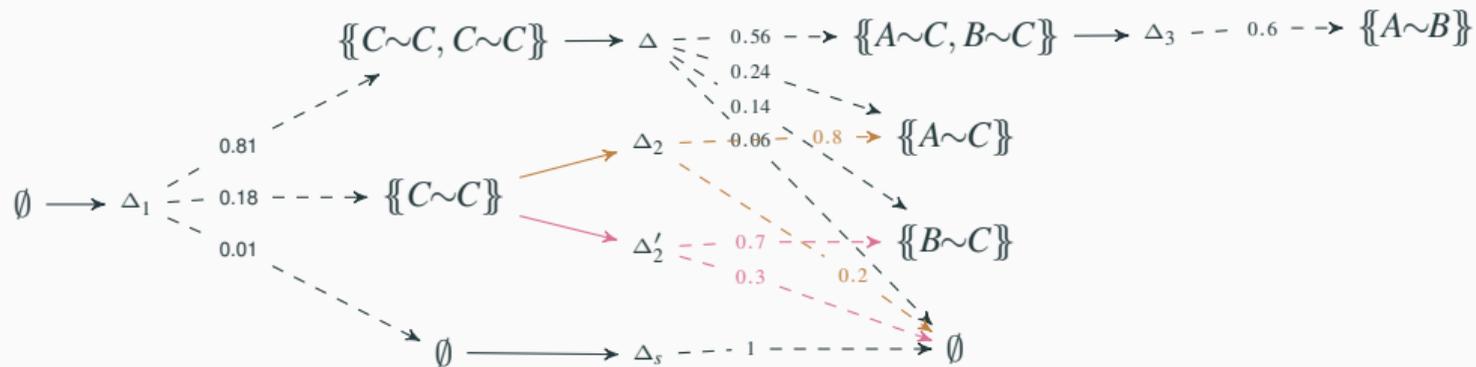
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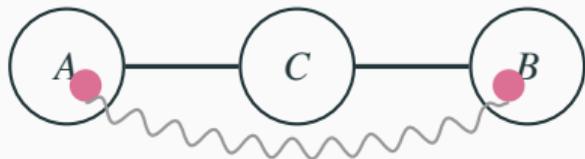
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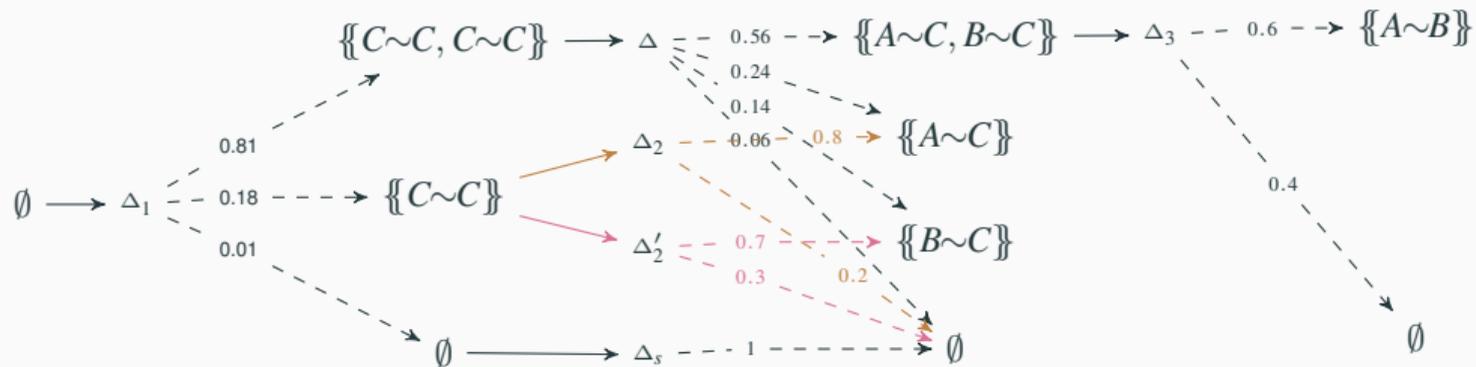
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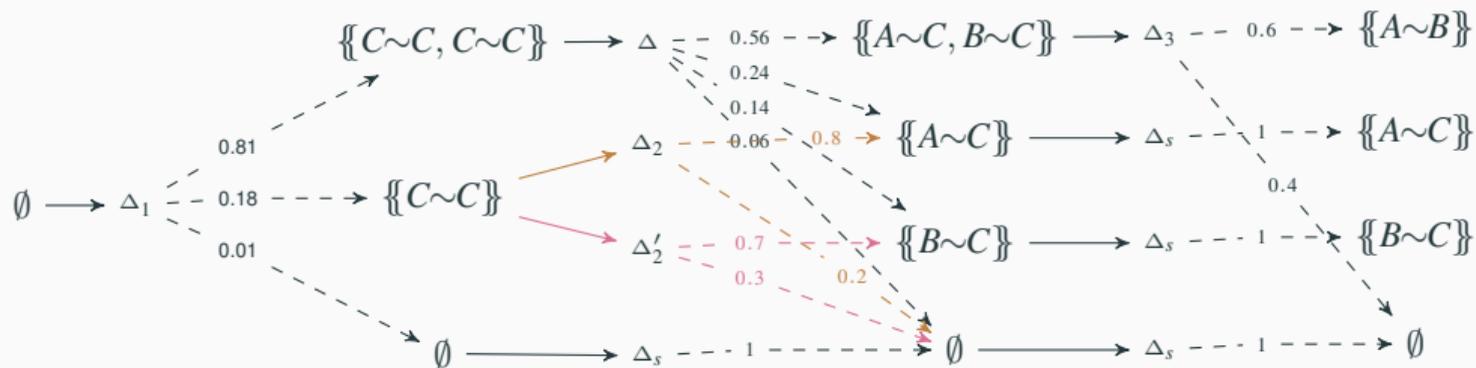


PBKAT protocol



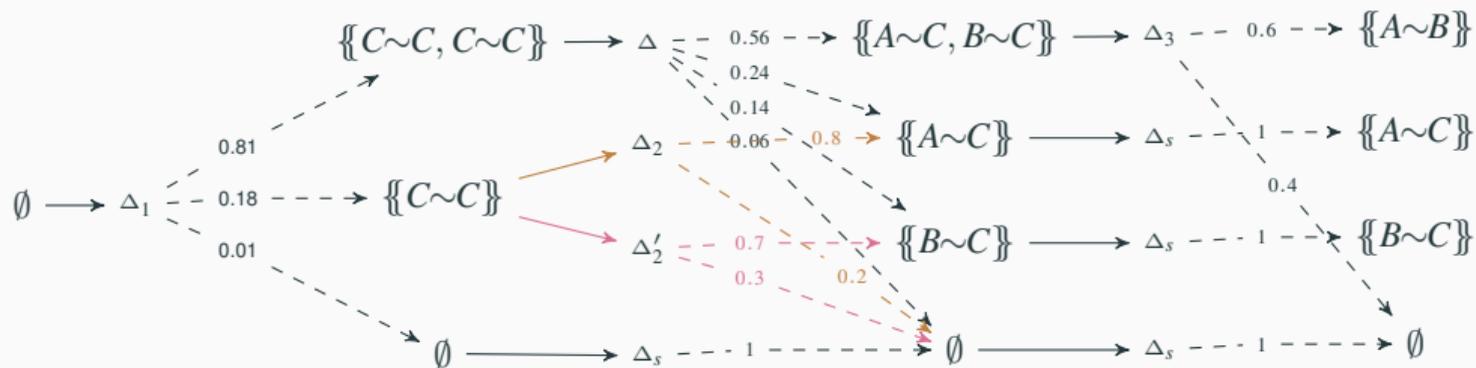
$(\text{cr}\langle C\sim C\rangle_{0.9} \parallel \text{cr}\langle C\sim C\rangle_{0.9}) ; (\text{tr}\langle C\rightarrow A\sim C\rangle_{0.8} \parallel \text{tr}\langle C\rightarrow B\sim C\rangle_{0.7}) ; \text{sw}\langle A\sim B @ C\rangle_{0.6}$

PBKAT protocol



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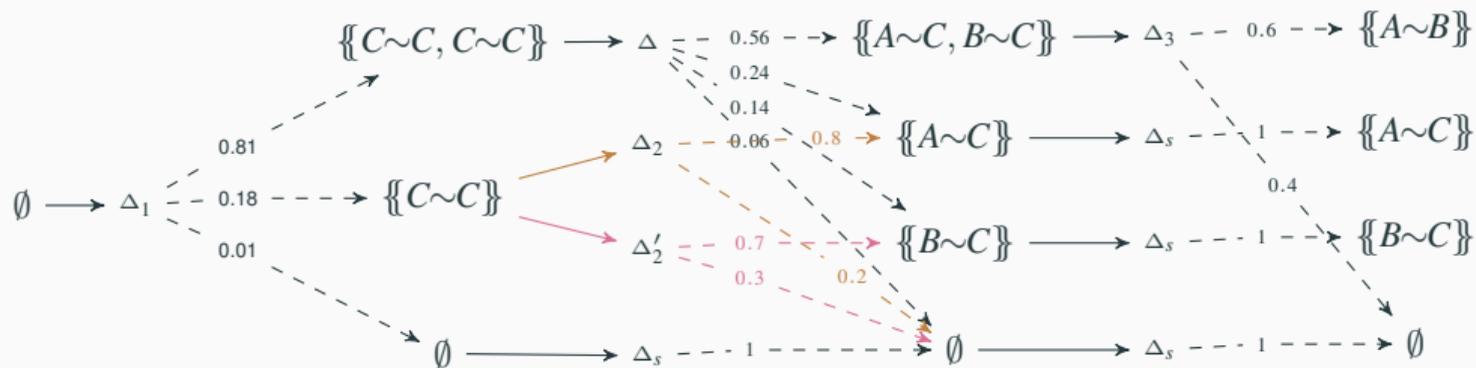


$$\mu = 0.27216 \cdot \{\{A \sim B\}\} + 0.1944 \cdot \{\{A \sim C\}\} + 0.2394 \cdot \{\{B \sim C\}\} + 0.29404 \cdot \emptyset$$

$$\mu' = 0.27216 \cdot \{\{A \sim B\}\} + 0.3384 \cdot \{\{A \sim C\}\} + 0.1134 \cdot \{\{B \sim C\}\} + 0.27604 \cdot \emptyset$$

Convex set of distributions: $\text{Conv}(\mu, \mu') = \{ q \cdot \mu + (1 - q) \cdot \mu' \mid q \in [0, 1] \}$

PBKAT protocol



$$\mu = 0.27216 \cdot \{\{A \sim B\}\} + 0.1944 \cdot \{\{A \sim C\}\} + 0.2394 \cdot \{\{B \sim C\}\} + 0.29404 \cdot \emptyset$$

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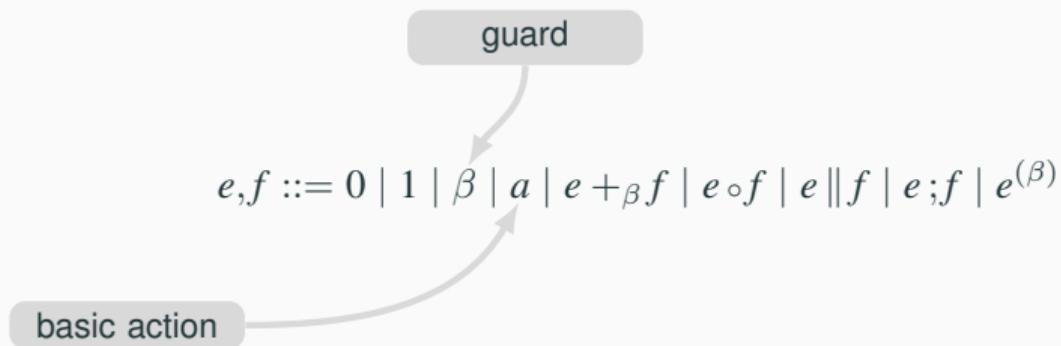
Convex set of distributions: $\text{Conv}(\mu, \mu') = \mu$  μ'

$$e, f ::= 0 \mid 1 \mid \beta \mid a \mid e +_{\beta} f \mid e \circ f \mid e \parallel f \mid e ; f \mid e^{(\beta)}$$

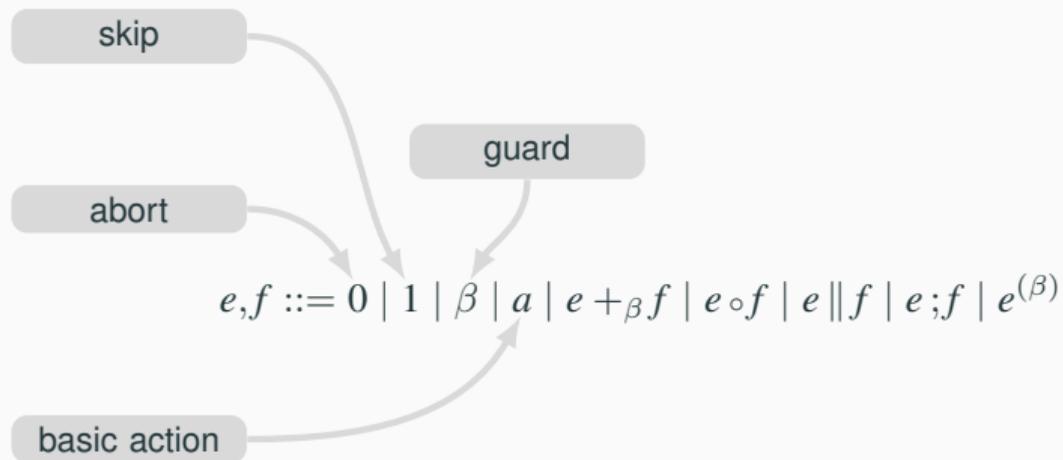
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basic action

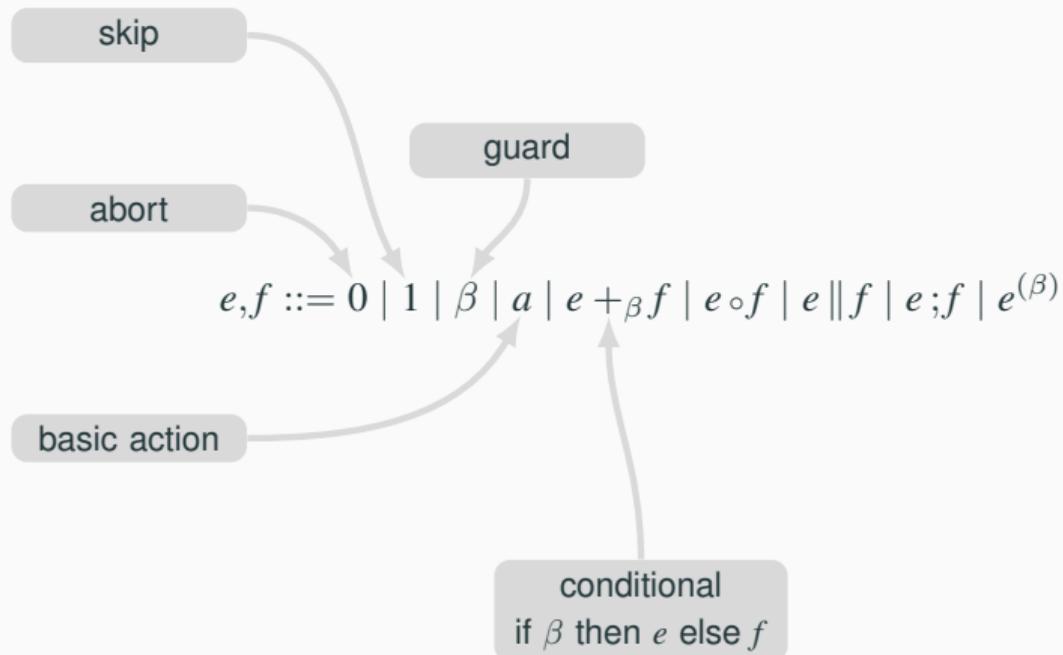




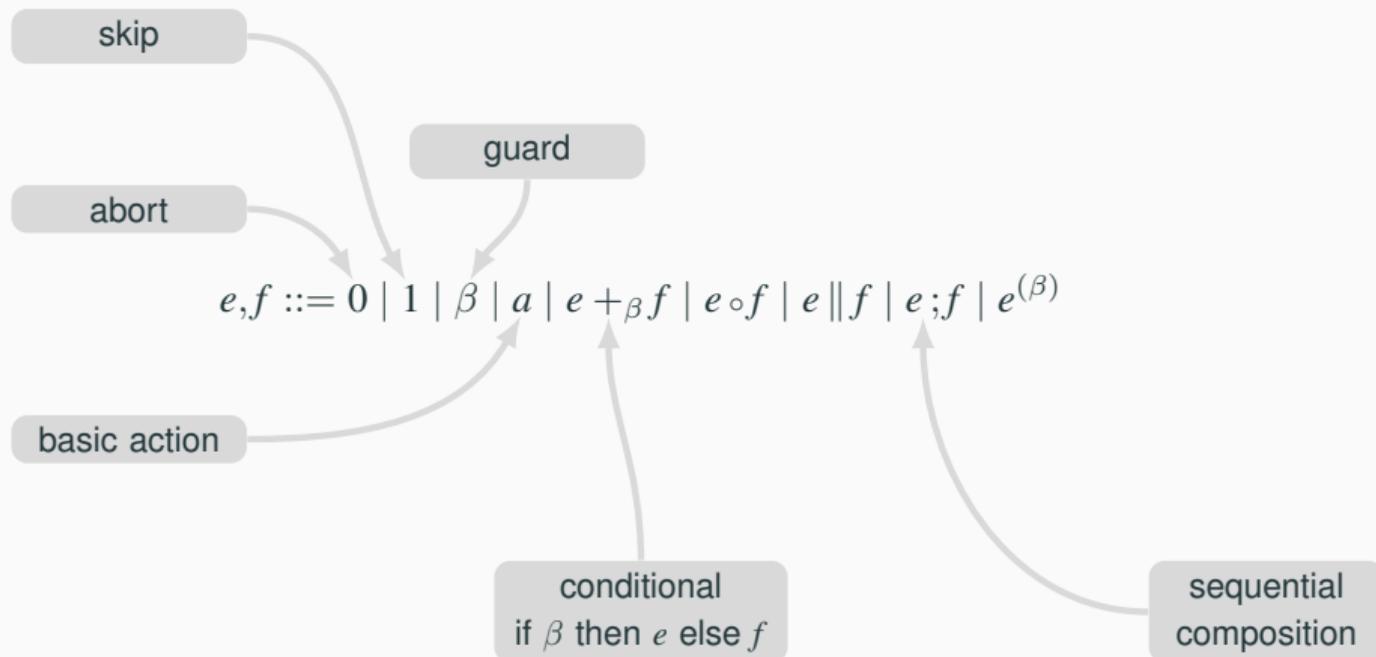
PBKAT syntax



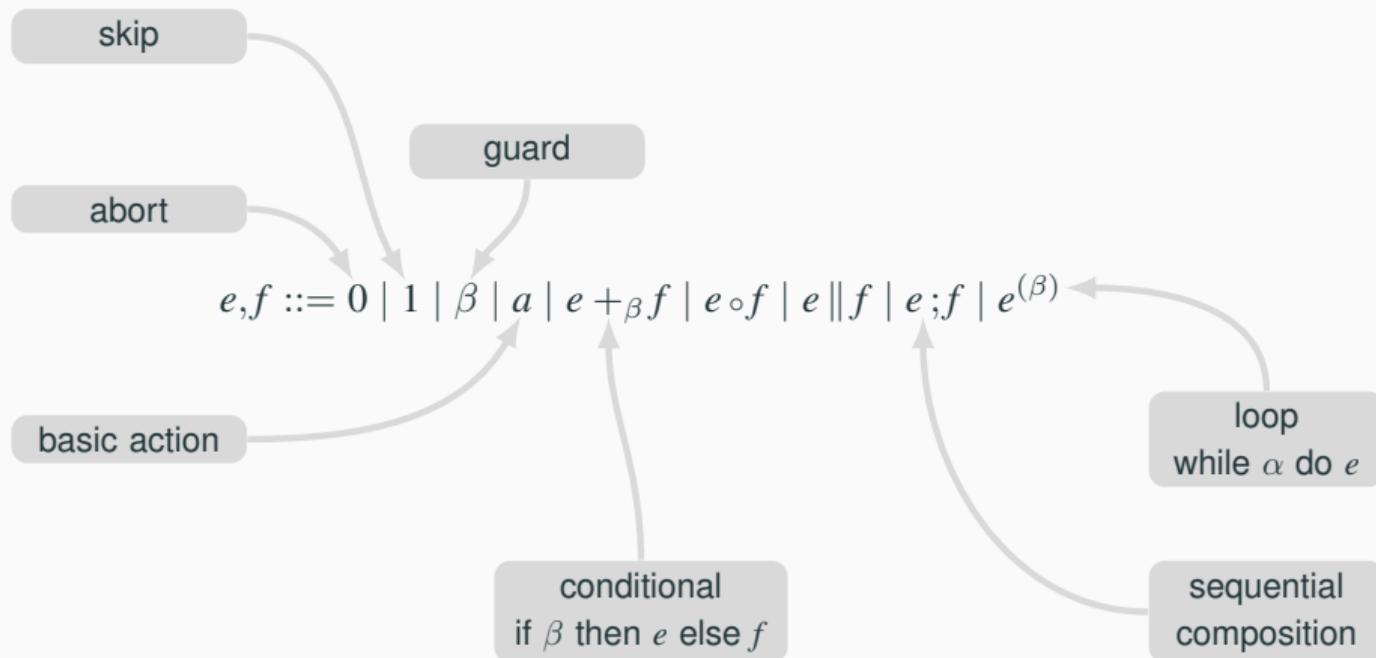
PBKAT syntax



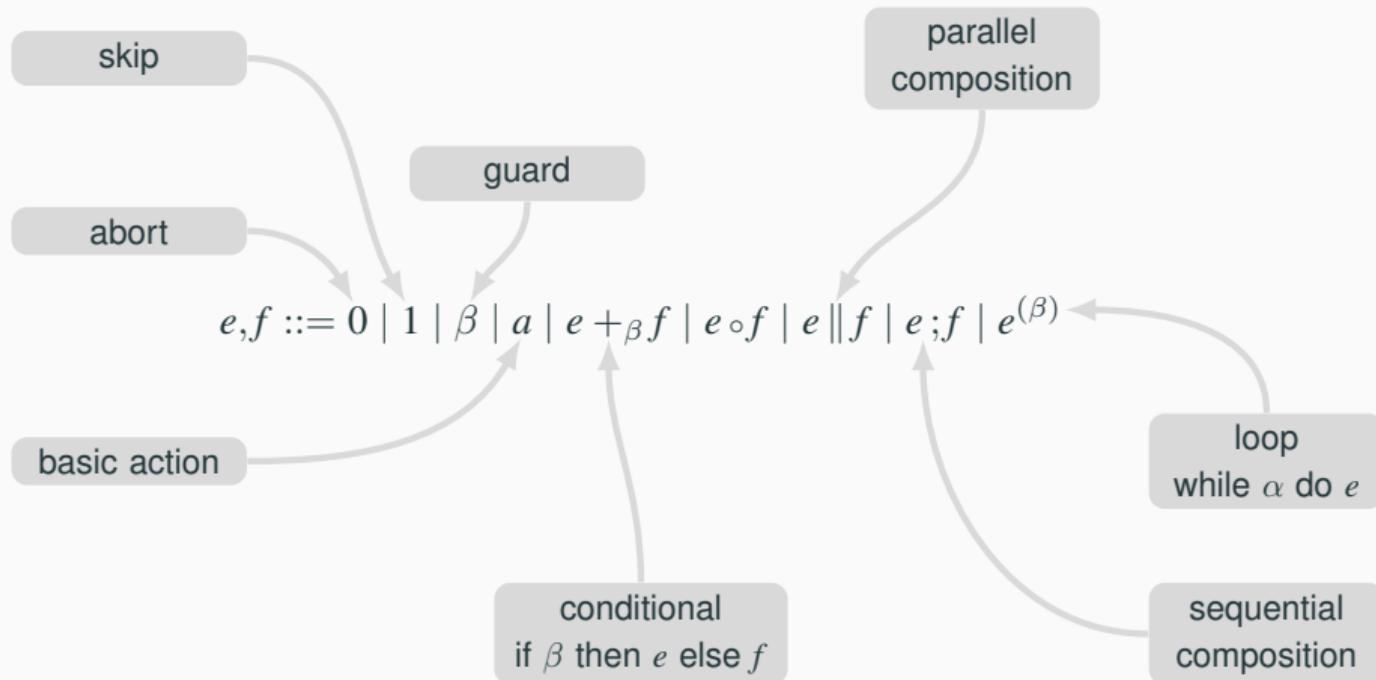
PBKAT syntax



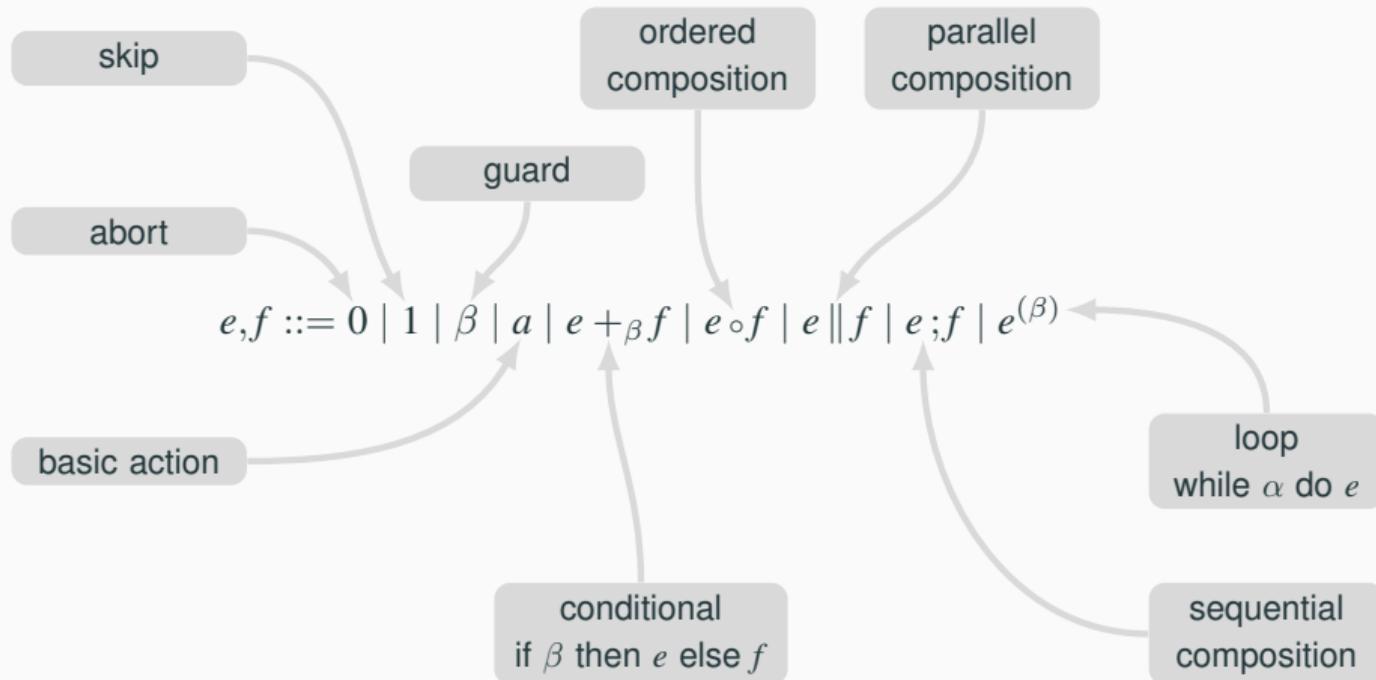
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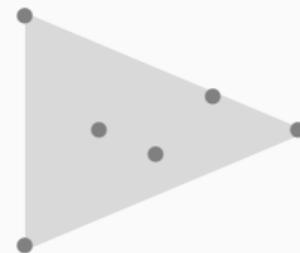
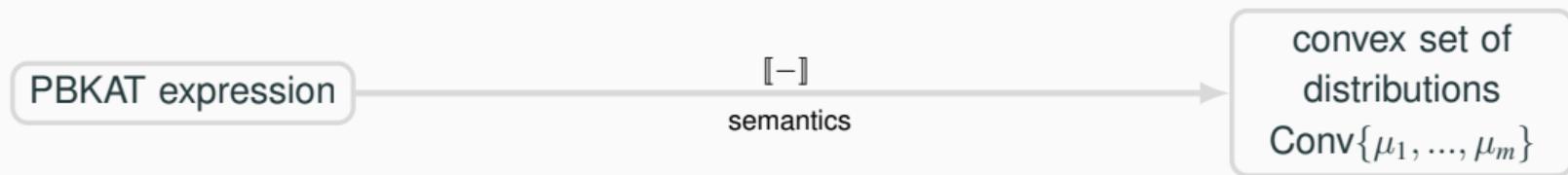
PBKAT syntax

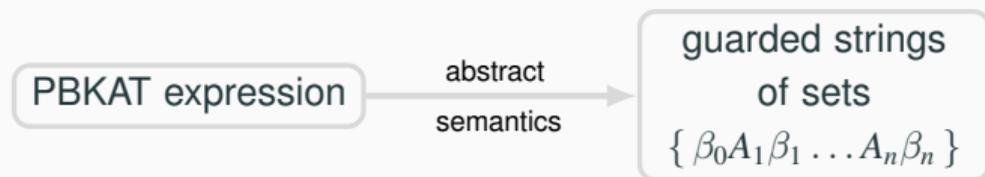


PBKAT syntax

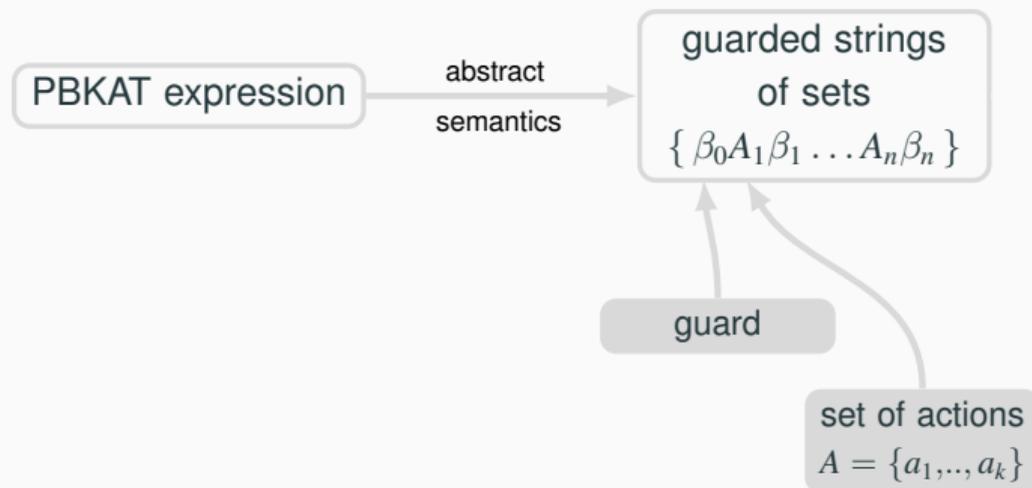


PBKAT semantics

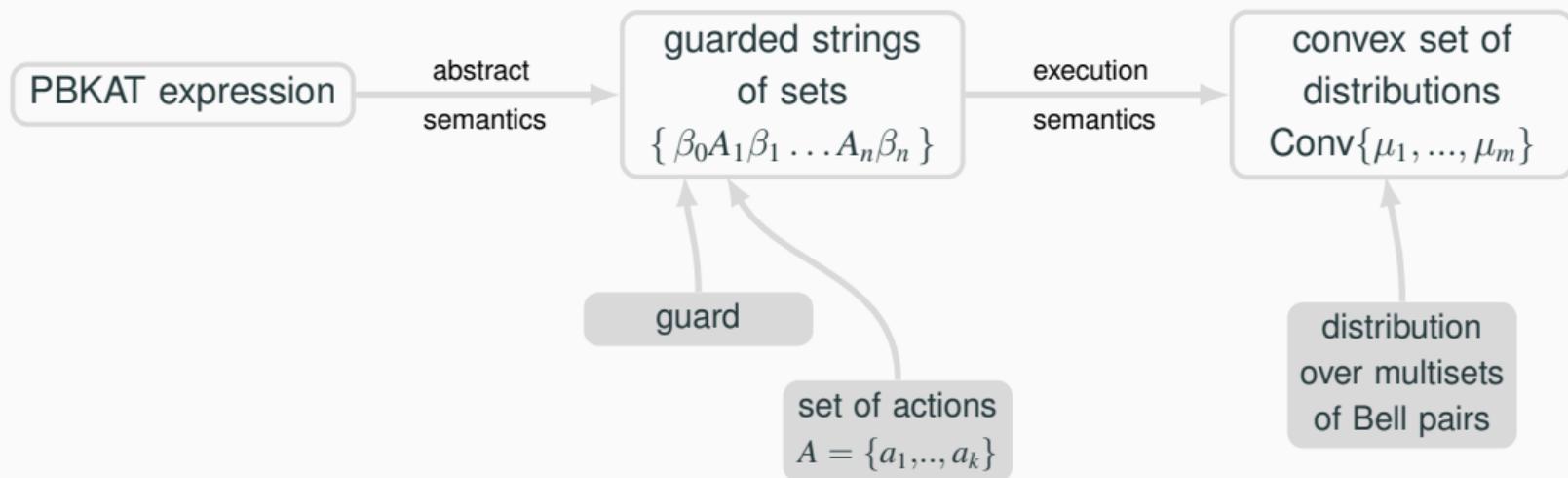




PBKAT semantics



PBKAT semantics



Write PBKAT expressions in an embedded DSL inside Haskell

```
f :: ProbBellKATPolicy
f = create "C" <> ite ("B" /~? "C") (trans "C" ("B", "C")) (trans "C" ("A", "C"))

p :: ProbBellKATPolicy
p = e <||> f
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- automaton capturing PBKAT's abstract semantics

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- automaton capturing PBKAT's abstract semantics
- execution traces

Write PBKAT expressions in an embedded DSL inside Haskell

```
cabal run probP5_1_I_parallel run
# (|×127 % 1000+|A~C|×117 % 250+|A~C,B~C|×81 % 250+|B~C|×81 % 1000,
#  |×181 % 1000+|A~C|×81 % 250+|A~C,B~C|×81 % 250+|B~C|×171 % 1000)
```

- automaton capturing PBKAT's abstract semantics
- execution traces
- convex set of probability distributions over multisets of Bell pairs

Summary

- PBKAT – language for expressing real-world quantum network protocols
- Soundness of PBKAT's axioms w.r.t. their corresponding semantics
- Enables protocol verification and optimization
- Prototype tool for quantitative analysis, evaluated on 16 protocols



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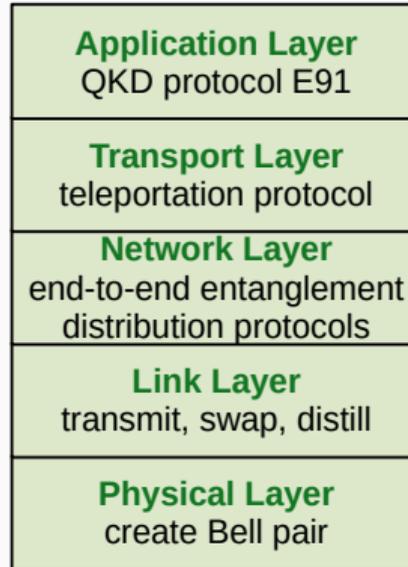


THANK YOU!

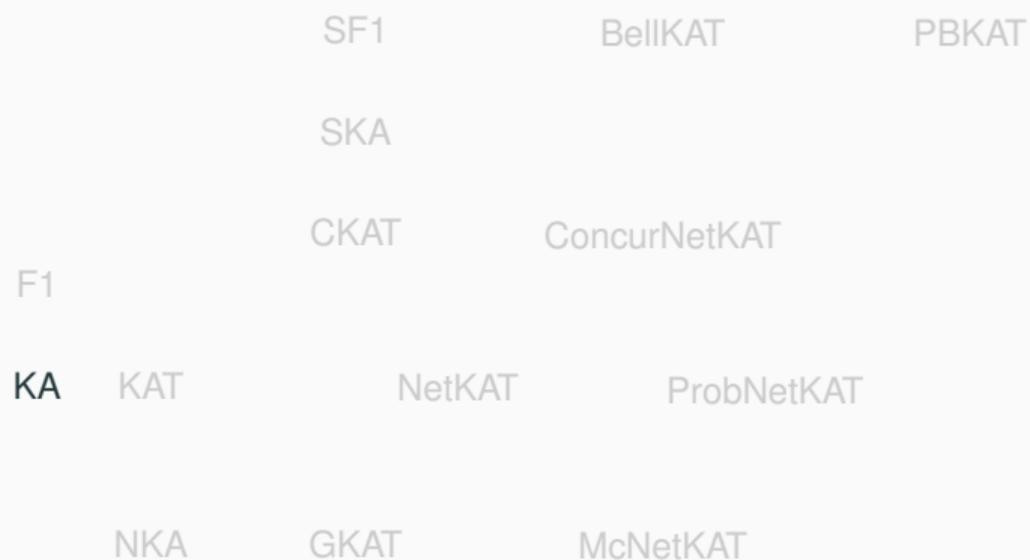
Evaluation

Protocol	Goal	PBKAT				BellKAT			
		Memory	Time	$ O $	$p(\text{Goal})$	Memory	Time	$ O $	Goal?
§3(a)	$\{A \sim B\}$	6 MiB	<1 s	2	27.2%	6 MiB	<1 s	4	maybe
§3(a ₁)	$\{A \sim B\}$	6 MiB	<1 s	1	27.2%	–	–	–	
Ex. 4.2	$\{A \sim B\}$	6 MiB	<1 s	2	10.7%	–	–	–	
Ex. 5.1(I), \circ	$\{A \sim C, B \sim C\}$	6 MiB	<1 s	1	32.4%	6 MiB	<1 s	4	maybe
Ex. 5.1(I), \parallel	$\{A \sim C, B \sim C\}$	6 MiB	<1 s	2	32.4%	6 MiB	<1 s	4	maybe
Ex. 5.1(II), \circ , 2 iter.	$\{A \sim C, B \sim C\}$	6 MiB	<1 s	1	61.9%	7 MiB	<1 s	9	maybe
Ex. 5.1(II), \parallel , 2 iter.	$\{A \sim C, B \sim C\}$	6 MiB	<1 s	14	60.7–67.8%	7 MiB	<1 s	9	maybe
Ex. 5.1(II), \circ , 3 iter.	$\{A \sim C, B \sim C\}$	6 MiB	<1 s	1	78.2%	8 MiB	<1 s	16	maybe
Ex. 5.1(II), \parallel , 3 iter.	$\{A \sim C, B \sim C\}$	24 MiB	26 s	22	77.4–85.2%	8 MiB	<1 s	16	maybe
Ex. 5.1(III), 1 iter.	$\{A \sim C, B \sim C\}$	6 MiB	<1 s	2	32.4%	–	–	–	
Ex. 5.1(III), 2 iter.	$\{A \sim C, B \sim C\}$	6 MiB	<1 s	2	76.6%	–	–	–	
Ex. 5.1(IV), 3 iter.	$\{A \sim C, B \sim C\}$	6 MiB	<1 s	2	92.7%	–	–	–	
§5.3(sw)	$\{A \sim B\}$	736 MiB	6 s	1	0.41%	–	–	–	
§5.3(di), outer	$\{A \sim B\}$	2263 MiB	15 s	1	<0.01%	–	–	–	
§5.3(di), inner	$\{A \sim B\}$	1178 MiB	8 s	1	0.11%	–	–	–	
§5.3(di), mixed	$\{A \sim B\}$	8271 MiB	377 s	1	0.02%	–	–	–	

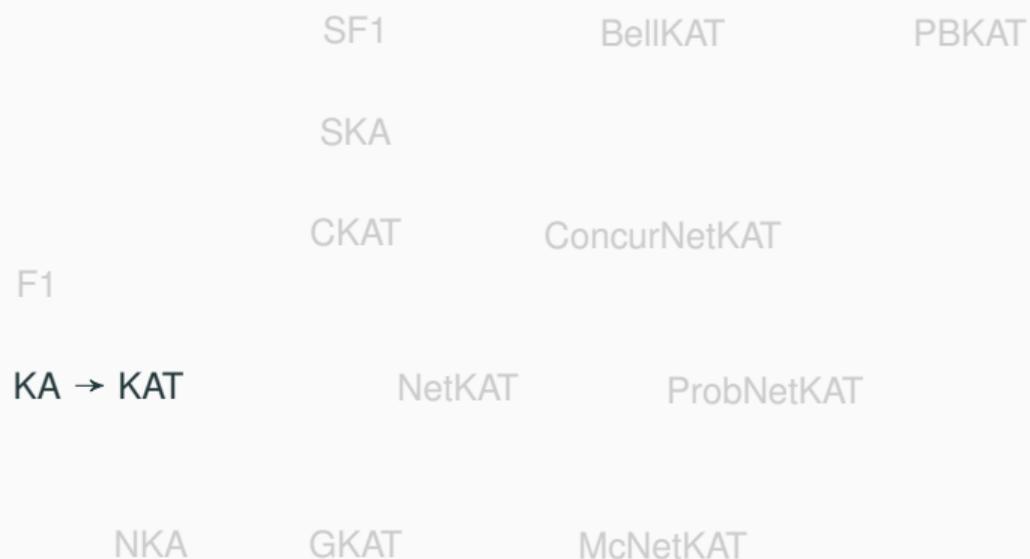
Quantum network protocol stack



Kleene algebras



Kleene algebras



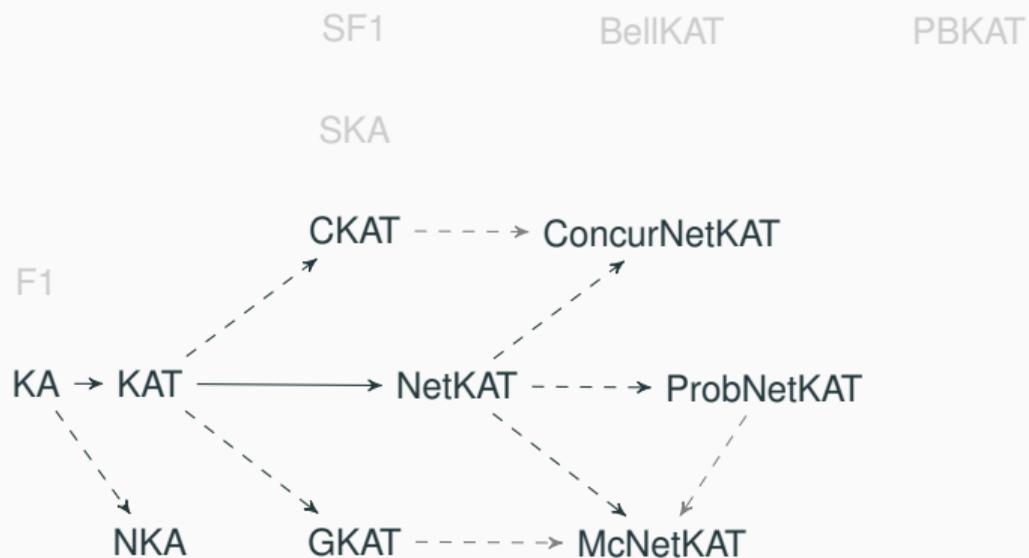
Kleene algebras



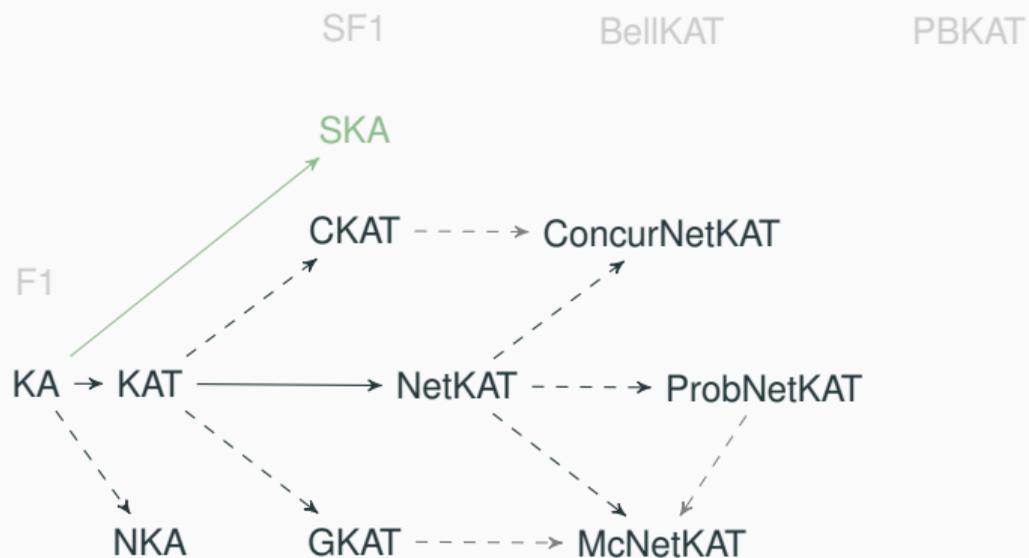
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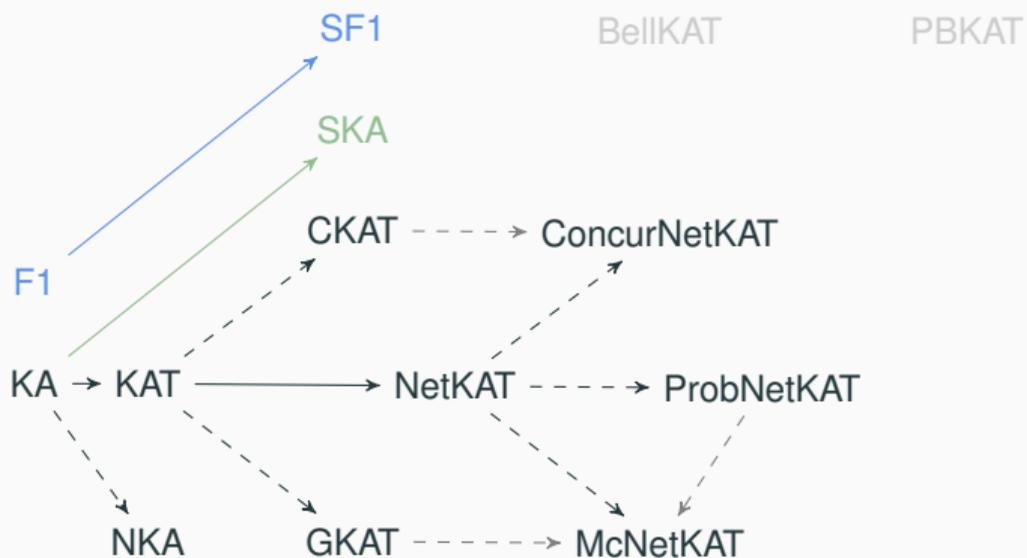
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