

*BC4IS @ CAiSE 2023*

*Zaragoza, Spain*

*12 June 2023*

# Blockchain for Information Systems

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## Blockchain Interoperability

Dr. Felix Härer

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UNIVERSITÉ DE FRIBOURG  
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DIGITALIZATION AND  
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[www.unifr.ch/inf/digits](http://www.unifr.ch/inf/digits)

# OUTLINE

- 1. Introduction - Open and Permissionless Blockchains**
- 2. Interoperability Challenges**
- 3. Cross-Chain Interoperability**
- 4. Interoperability Beyond Blockchains**
- 5. Conclusion**

# SPEAKER

Dr. Felix Härer

Senior Researcher and Lecturer

Digitalization and Information Systems Group

University of Fribourg, Switzerland



## Background

- PhD in Information Systems, on Decentralization and Blockchains
- BSc and MSc in Information Systems, Cyber Security MSc specialization
- Industry experience in Software Engineering (Siemens Healthcare, research projects)

[www.unifr.ch/inf/digits/en/  
group/team/haerer.html](http://www.unifr.ch/inf/digits/en/group/team/haerer.html)

## Current Events

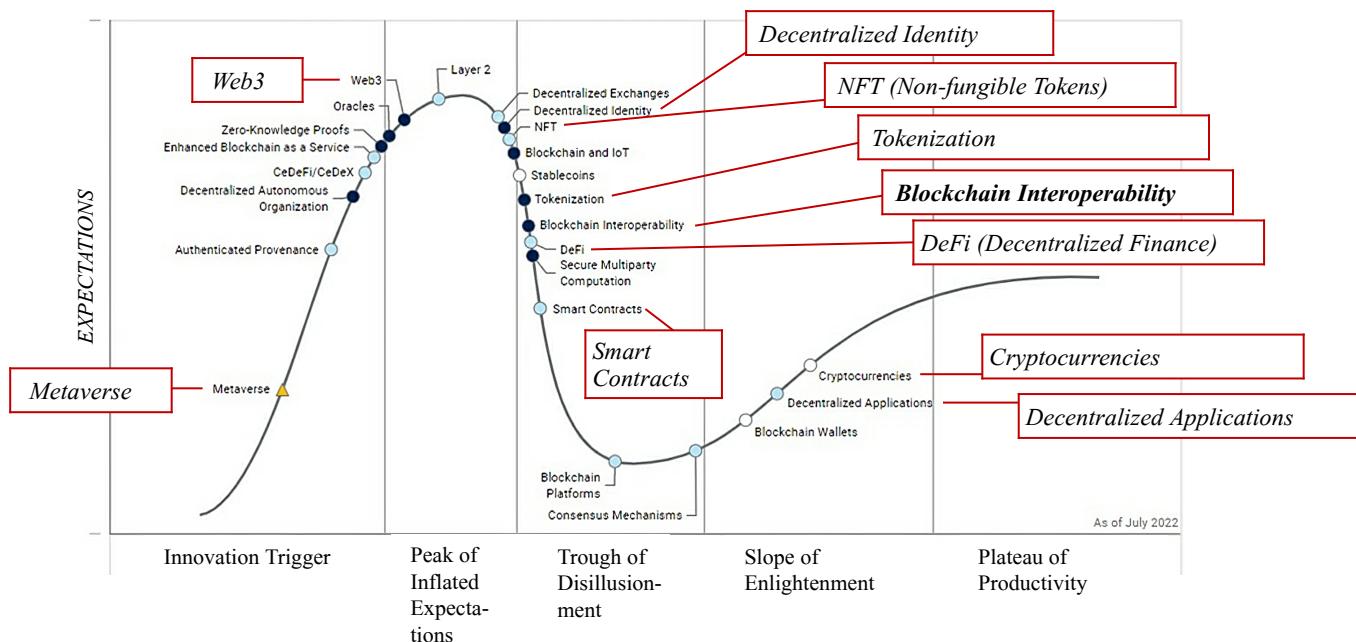
- SI Business Informatics Blockchain Forum (online)  
[unifr.ch/inf/digits/events](http://unifr.ch/inf/digits/events)
- 3rd International Workshop on Blockchain for Trusted Data Sharing, B4TDS @ BIR 2023, Ascoli Piceno, Italy  
[pros.unicam.it/B4TDS2023](http://pros.unicam.it/B4TDS2023)

## Recent Publications

- Curty, S., Härer, F. & Fill, HG: Design of blockchain-based applications using model-driven engineering and low-code/no-code platforms: a structured literature review. *Softw Syst Model* (2023)
- Härer, F.: Towards Interoperability of Open and Permissionless Blockchains: A Cross-Chain Query Language, in: *Proceedings of the 2022 IEEE International Conference on E-Business Engineering (IEEE ICEBE 2022)*, 2022, Bournemouth, UK.

# BLOCKCHAIN TRENDS

## Blockchain Technology According to the "Hype Cycle for Blockchains and Web3, 2022" (Gartner)



July 2022

<https://blogs.gartner.com/avivah-litan/2022/07/22/gartner-hype-cycle-for-blockchain-and-web3-2022/>

# BLOCKCHAIN AND CRYPTOCURRENCY

## Cryptocurrency

#	Name	Price	1h %	24h %	7d %	Market Cap ⓘ
1	Bitcoin BTC	\$26,074.20	▲ 0.33%	▲ 1.64%	▼ 4.21%	\$505,826,567,570
2	Ethereum ETH	\$1,765.35	▲ 0.36%	▲ 1.40%	▼ 7.31%	\$212,243,796,012
3	Tether USDT	\$1.00	▼ 0.01%	▼ 0.00%	▲ 0.03%	\$83,415,305,049
4	BNB BNB	\$237.80	▲ 0.35%	▼ 0.07%	▼ 22.31%	\$37,062,041,317
5	USD Coin USDC	\$1.00	▲ 0.00%	▲ 0.01%	▲ 0.03%	\$28,387,926,951
6	XRP XRP	\$0.5274	▲ 1.21%	▲ 4.72%	▼ 1.79%	\$27,417,559,144
7	Cardano ADA	\$0.2729	▲ 0.75%	▲ 3.36%	▼ 28.39%	\$9,526,493,528
8	Dogecoin DOGE	\$0.06218	▲ 0.14%	▲ 1.95%	▼ 14.70%	\$8,687,740,868
9	TRON TRX	\$0.07033	▲ 0.23%	▲ 1.37%	▼ 14.09%	\$6,337,870,651

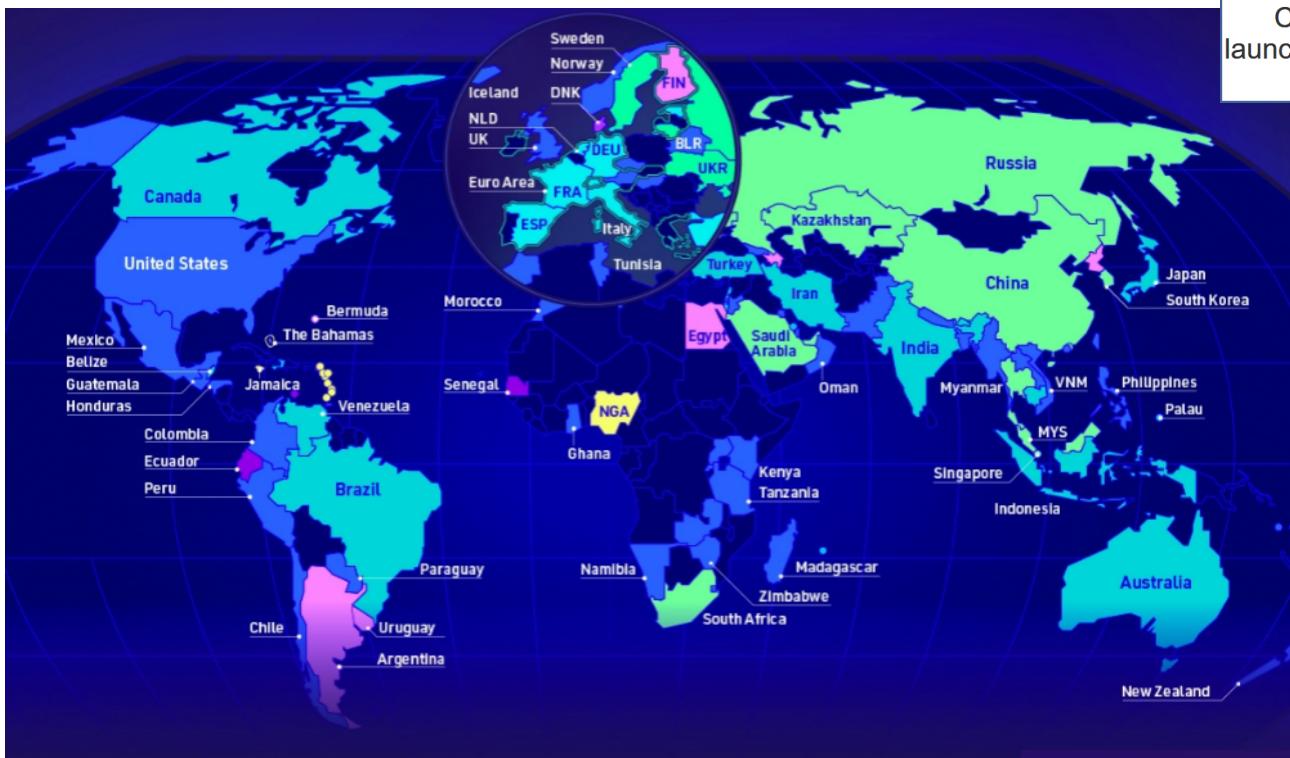
## Companies

Rank	↑	Name	Market Cap
1	▲	Apple AAPL	\$2.846 T
2	▲	Microsoft MSFT	\$2.429 T
3	▲	Saudi Aramco 2222.SR	\$2.097 T
4	▲	Alphabet (Google) GOOG	\$1.622 T
5	▲	Amazon AMZN	\$1.274 T
6	▲	NVIDIA NVDA	\$957.61 B
7	▲	Tesla TSLA	\$774.62 B
8	▲	Berkshire Hathaway BRK-B	\$733.77 B
9	▲	Meta Platforms (Facebook) META	\$695.77 B
10	▲	TSMC TSM	\$533.16 B
11	▲	Visa V	\$479.07 B
12	▲	UnitedHealth UNH	\$459.57 B

coinmarketcap.com

companies-  
marketcap.com

# CENTRAL BANK DIGITAL CURRENCIES (CBDC)



Data: Atlantic Council, CBDC Tracker (2022), Visualization:

<https://www.visualcapitalist.com/visualized-the-state-of-central-bank-digital-currencies/>

SNB: [https://www.snb.ch/de/ifor/research/conf/other\\_academic\\_conferences/id/sem\\_2022\\_06\\_03](https://www.snb.ch/de/ifor/research/conf/other_academic_conferences/id/sem_2022_06_03)

ECB Report August 2022: <https://www.ecb.europa.eu/pub/pdf/scpwps/ecb.wp2713~91ddff9e7c.en.pdf>

Ministry of Finance



Central Bank Digital Currency (CBDC) pilot launched by RBI in retail segment has components based on blockchain technology

<https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1882883>



eCNY

<https://www.chinainternetwatch.com/33050/cbdc-ecny/>  
<https://www.nytimes.com/2021/03/01/technology/china-national-digital-currency.html>

STATUS			
	<b>Launched</b>	Issued a CBDC for widespread retail and/or wholesale use.	
	<b>Pilot</b>	Initiated small-scale testing of a CBDC in the real world with a limited number of participants.	
	<b>Development</b>	Initiated technical build and early testing of a CBDC in a controlled environment.	
	<b>Research</b>	Started exploring the use cases, impact and feasibility of a CBDC.	
	<b>Inactive</b>	CBDC initiative is on hold.	
	<b>Canceled</b>	CBDC initiative decommissioned.	

# TOKENIZATION

## Framework

	Currency			Token			
Unit	Fungible Coins			Fungible / Non-fungible Tokens		Non-fungible Tokens	
Representation	Crypto-currency	Stablecoin algorithmic	private	Central Bank Digital C.	Asset / Security / Equity	Utility	
Issuance and Supply	Decentralized and algorithmic	Private Firm(s)	Central Bank(s)	Asset Management and Investment Firms	Decentralized and algorithmic	Decentralized and algorithmic, issuance often centralized	
Technology	Blockchain	Blockchain w/ Smart Contracts	Blockchain / other IT	Blockchain w/ Smart Contracts operate accounts, transfer fees, shares of ownership, interest etc.			
Examples	Bitcoin, Ether	DAI	USDC USDT	e₹-W e₹-R eCNY	SEBA Security Tokens PAXG (Gold-backed token)	Link (provides data on-chain), Graph, Golem (computation)	artèQ, OpenSea (tokenized art), Decentraland, Sandbox (avatars, land, objects in virtual worlds ("metaverse"))

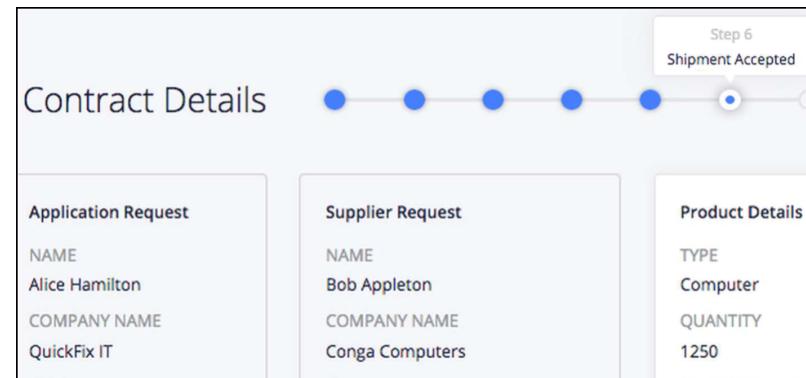
Adapted in 01/2023 from  
 "Kryptowährungen" (Härer, 2019) in:  
 Blockchain Kompakt, Springer (2019)

e₹-W:  
 Digital Rupee – Wholesale  
 e₹-W: Digital Rupee - Retail  
<https://pib.gov.in/PressReleaselframePage.aspx?PRID=1882883>

# SMART CONTRACT AND DECENTRALIZED APPS (DAPPS)

## Example Applications

- **Attestation of Documents and Identities, Notarization**
- **Decentralized Web / web3**
- **Business Process Management**
- **Supply chain tracking**
- **IoT**
- **Healthcare and Pharma**



Example of Supply Chain Tracking using Hyperledger

# DISTRIBUTED SYSTEMS

- Today, open and public blockchains are emerging as globally distributed systems
- Largest open and permissionless blockchains by approx. number of network nodes

— Bitcoin	 15 000
— Ethereum	 6 000
— Cardano	 3 000
— Solana	 1 600
— Avalanche	 1 300

Data collected in August 2022

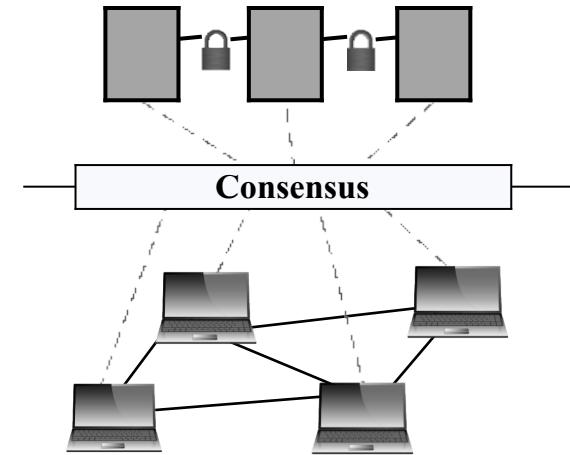


Distribution of Bitcoin nodes ([bitnodes.io](https://bitnodes.io))

# OPEN AND PERMISSIONLESS BLOCKCHAINS

## Blockchain System Components

- **Data Structure:**  
Ledger of transactions
- **Consensus:**  
Mechanisms and algorithms, at least for distribution, security, scalability, incentivization
- **Network Nodes:**  
Participants executing consensus



### Terminology

- Distribution: distribution across the network
- Decentralized: without centralized coordination
- Blockchain: the data structure component, in practice also used for the system

# OPEN AND PERMISSIONLESS BLOCKCHAINS

## Open and Permissionless Blockchain Platforms in 2023

by Number of Participants / Network Nodes

Blockchain	Data Structure	Network	Consensus Protocol	Smart Contract Features	
	[1] Bitcoin <sup>a</sup>	Blocks, UTXO data model	Bitcoin, approx. 15000 nodes	Nakamoto Consensus, Proof-of-Work	Stack-based script execution, monetary transactions
	[2] Ethereum <sup>b</sup>	Blocks, account state storage in tree data structures	Ethereum Mainnet, approx. 6000 nodes	Proof-of-Stake	Ethereum Virtual Machine, general-purpose programs
	[3] Cardano <sup>c</sup>	Blocks, extended UTXO model	Cardano, approx. 3000 nodes	Ouroboros, Proof-of-Stake	General-purpose programs, functional
	[4] Solana <sup>d</sup>	Block and graph data structures over different time spans	Solana Mainnet Beta, approx. 1600 nodes	Graph-based (proof-of-history), Proof-of-Stake	General-purpose programs
	[5] Avalanche <sup>e</sup>	Block and graph data structures over different networks	Platform/Exchange/Contract (P/X/C) chain, approx. 1300 nodes	Avalanche (P Chain) Snowman (X/C Chain), Proof-of-Stake	Ethereum Virtual Machine (C Chain), general-purpose programs

a <https://bitnodes.io/>

b <https://ethereum.org/en/developers/docs/>, <https://ethernodes.org/>

c <https://adastat.net/pools/>

d <https://docs.solana.com>, <https://solanabeach.io/validators/>

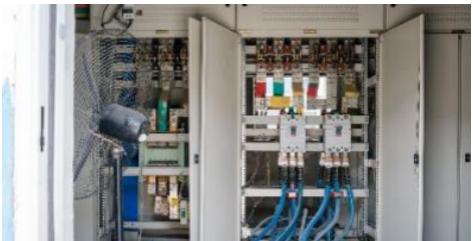
e <https://stats.avax.network/dashboard/network-status/>

Table: Adapted from Härrer (2022): Towards Interoperability of Open and Permissionless Blockchains: A Cross-Chain Query Language. In publication.

# OPEN AND PERMISSIONLESS BLOCKCHAINS

## Decentralization - Bitcoin

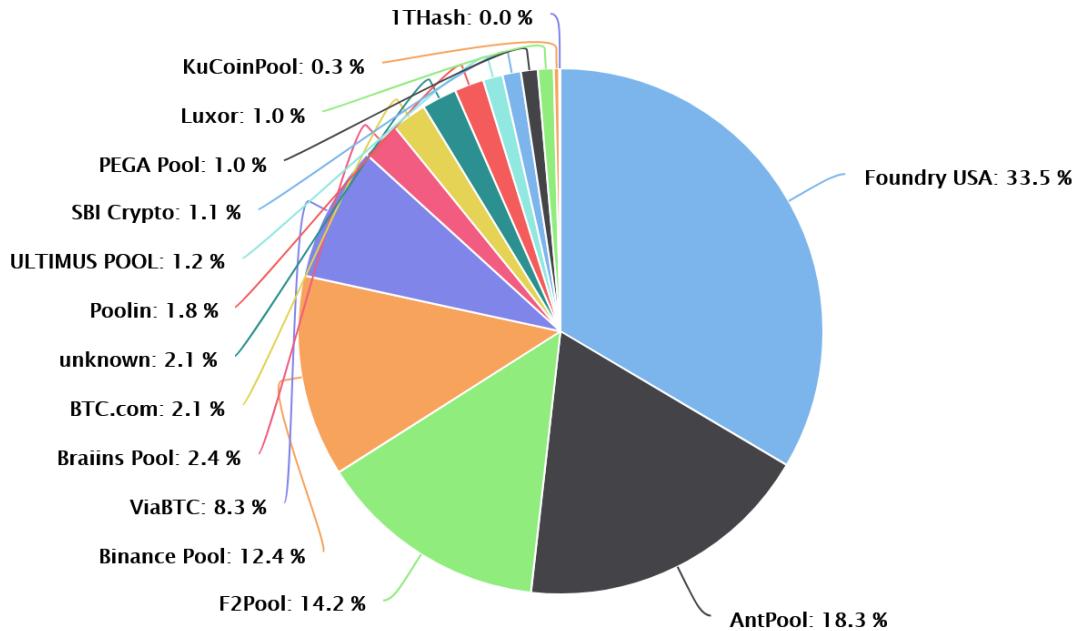
### Bitcoin Mining



Nodes  
Specialized  
ASIC  
Miner  
Hardware

### Distribution

Nodes operating in mining pools



[https://btc.com/stats/pool?pool\\_mode=month](https://btc.com/stats/pool?pool_mode=month)

Feb 2023, Timespan: 1 Month

# OPEN AND PERMISSIONLESS BLOCKCHAINS

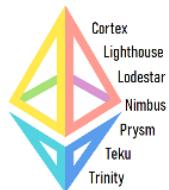
## Decentralization - Ethereum

### Ethereum Staking

Nodes



Low-power PCs



Node Software  
in multiple  
implementations



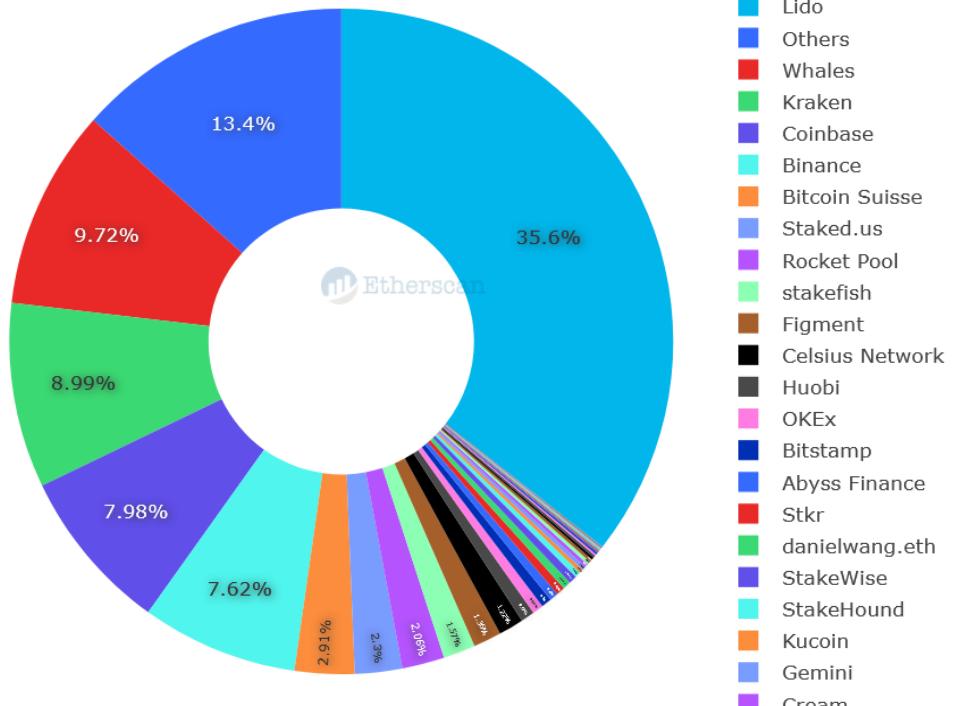
Cloud  
Servers



Virtual Machine  
Nodes

### Distribution of Nodes

Nodes with deposits (staking) on Ethereum



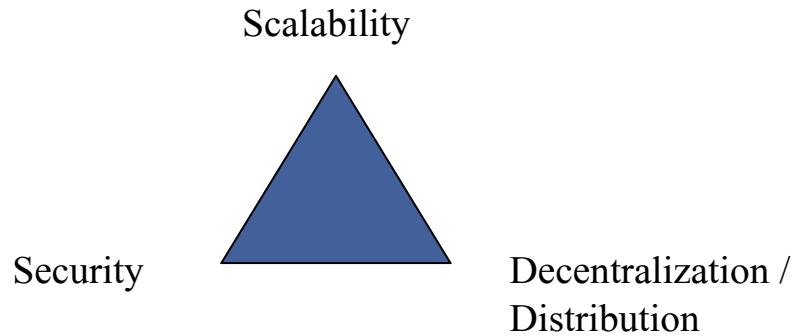
[https://bi.etherscan.io/public/dashboards/KH9jbP687szqlAnHiNEfNictrwNhvdOEQl0PwB6m?org\\_slug=default](https://bi.etherscan.io/public/dashboards/KH9jbP687szqlAnHiNEfNictrwNhvdOEQl0PwB6m?org_slug=default)

Feb 2023

# OPEN AND PERMISSIONLESS BLOCKCHAINS

## Blockchain Properties

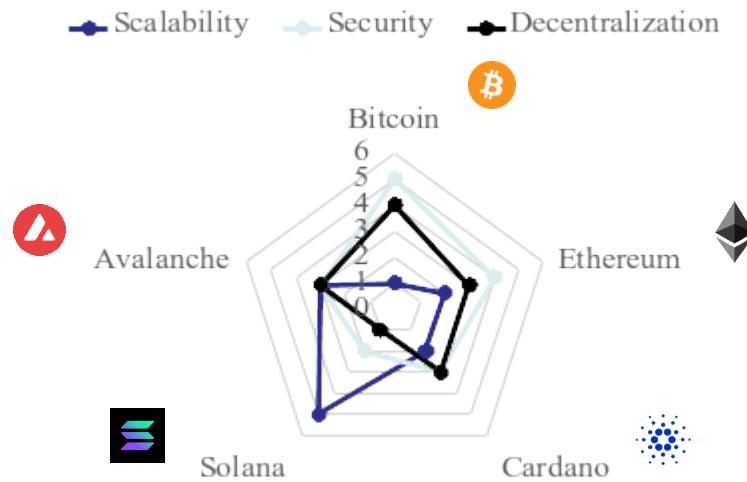
Blockchains *internally* guarantee certain properties to varying degrees



Blockchain trilemma and variants suggested by Zooko Wilcox and others

# OPEN AND PERMISSIONLESS BLOCKCHAINS

## Blockchain Properties



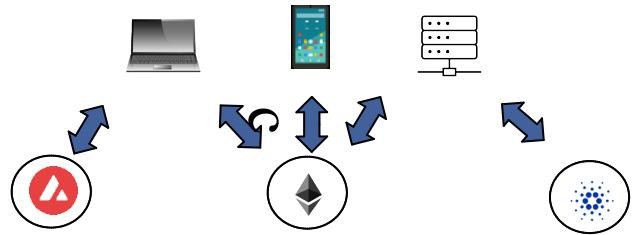
Estimation of factors for well-known blockchains

Based on factors from Härer (2022): Towards Interoperability of Open and Permissionless Blockchains: A Cross-Chain Query Language. In publication.

# INTEROPERABILITY CHALLENGE

## The Ultimate Application Platform?

- Open and permissionless blockchains provide unique properties on a technical level
  - Novel consensus and incentivization mechanisms
  - Transactions with a-priori unknown parties
  - Transactions without Trusted Third Parties
  - Verifiability and transparency
  - Guarantees: varying degrees of decentralization, security, scalability
- Properties, features, trade-offs differ considerably

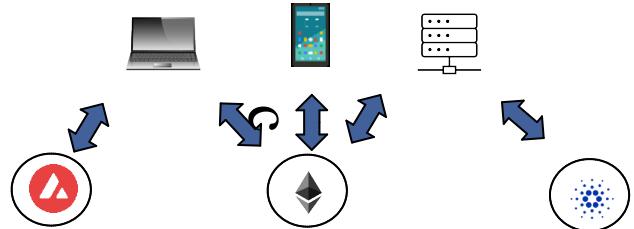


# INTEROPERABILITY CHALLENGE

## Interoperability Challenge

1. No interoperability on a technical level

=> Cross-Chain Interoperability?



2. No interoperability beyond blockchains

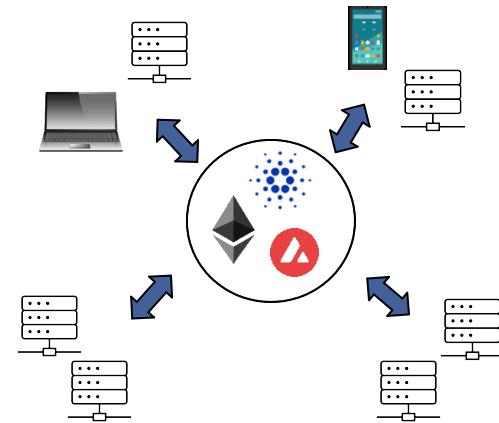
=> Real-World Applications?

**Blockchains as universal application platforms for storage and computation?**

# CHROSS-CHAIN INTEROPERABILITY

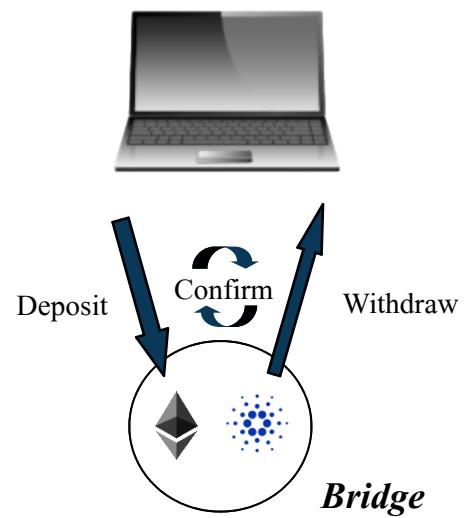
## Bridges

- Connection of isolated networks
- Transfer of standardized tokens, data, function calls for smart contracts
- Adapter paradigm, n-to-n complexity
- Applied for blockchains, sidechains, layer 2 (Channels, Roll-Ups, Zero-Knowledge)



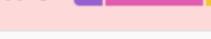
# CHROSS-CHAIN INTEROPERABILITY

## Bridges



# CHROSS-CHAIN INTEROPERABILITY

## Bridges in Practice

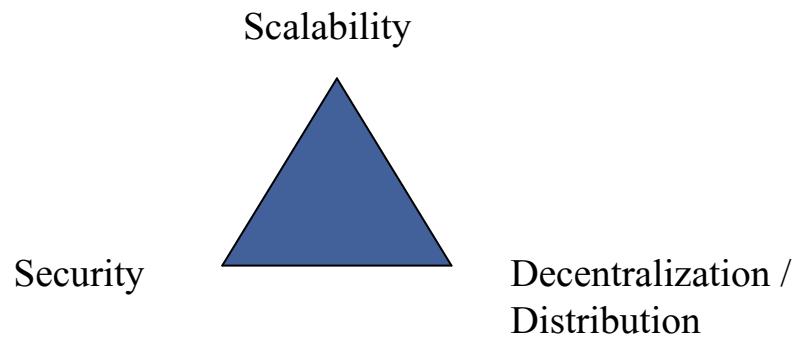
#	NAME	TVL ⓘ	7D CHANGE ⓘ	BREAKDOWN ⓘ	MKT SHARE ⓘ
1	♾️ Polygon PoS	\$2.07B	▼ 5.13%		42.22%
2	♾️ Polygon "Plasma"	\$614M	▼ 26.88%		12.49%
3	🛡️ Ronin V2	\$521M	▼ 27.35%		10.60%
4	▲ Avalanche Bridge	\$377M	▼ 5.46%		7.67%
5	▣ Rainbow Bridge	\$200M	▼ 7.52%		4.07%
6	◎ Portal (Wormhole)	\$158M	▼ 8.89%		3.22%
7	♾️ Multichain ⚡	\$154M	▼ 25.34%		3.15%
8	之心 PulseChain	\$127M	▼ 5.07%		2.60%
9	⌚ Orbit Bridge ✖️	\$102M	▼ 4.17%		2.09%
10	📡 Satellite (Axelar)	\$94.89M	▲ 6.20%		1.93%

<https://l2beat.com/bridges/tvl#active>

# CHROSS-CHAIN INTEROPERABILITY

## Bridges - Limitations

- Tokens need to be defined in both chains, minting or reserves needed
- Smart contracts need to exist with well-known addresses in both chains
- Centralization risk
- Security risk
- Usually no distribution (e.g. multi-signature)
- N-to-n complexity
- Usually no atomic cross-chain swaps (locking of tokens, e.g. HTLC)



# CHROSS-CHAIN INTEROPERABILITY

## Bridges - Limitations

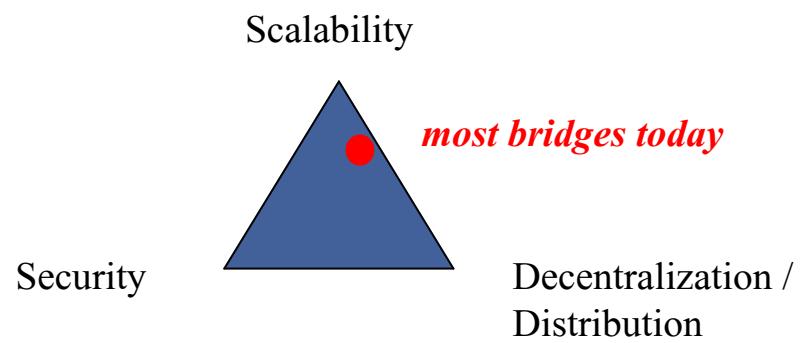
Bridge exploits account for ~50% of exploited funds in decentralized finance

(A. Fletcher, beamerbridge.com)

### Recent Examples

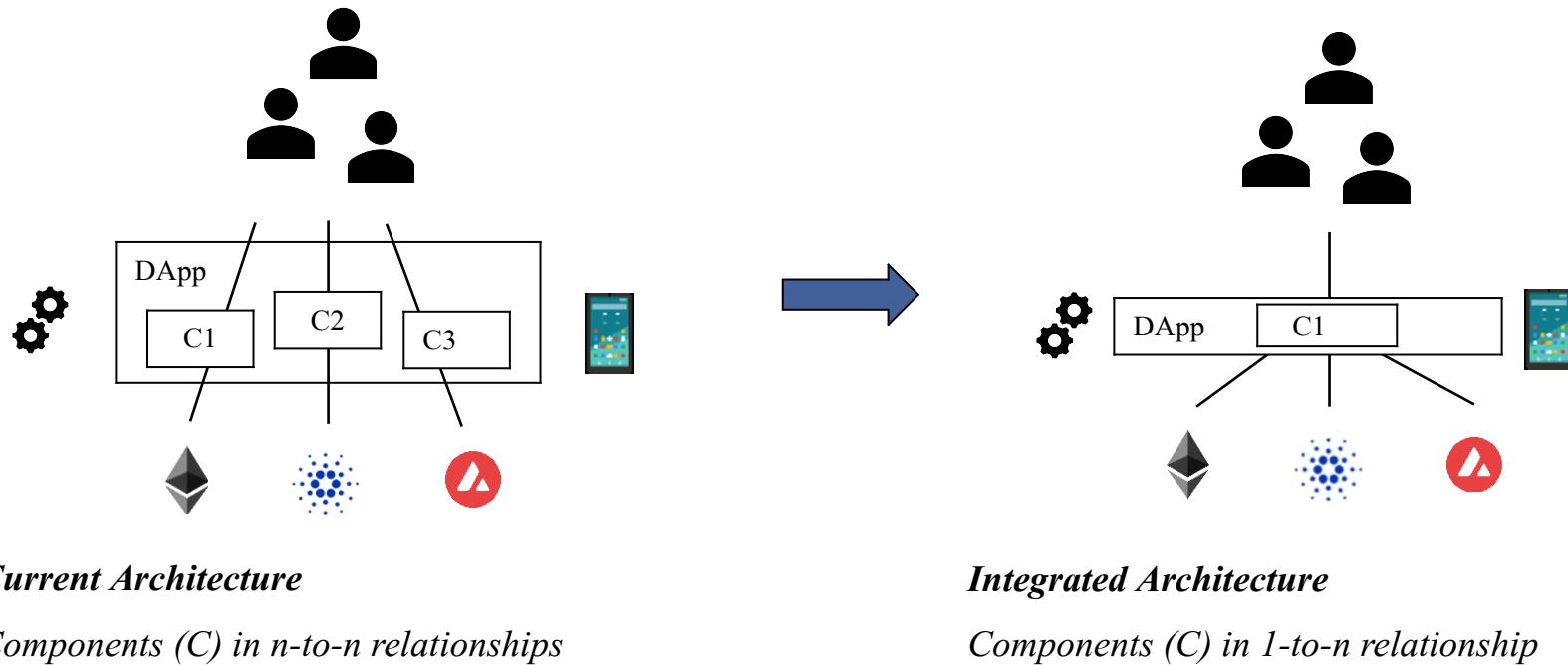
- Harmony Bridge: ~100M USD
- Ronin Bridge: ~600M USD
- Poly Network: ~600M USD

(Zamyatin, Imperial College London)



# CROSS-CHAIN QUERY LANGUAGE

## Application Level Interoperability



# CROSS-CHAIN QUERY LANGUAGE

## Research Design of a Cross-Chain Query Language

### Common data model

- Portability, compatibility, and migration advantages for software using blockchains

### Standardized Syntax

- Abstract from implementation

### Processing architecture

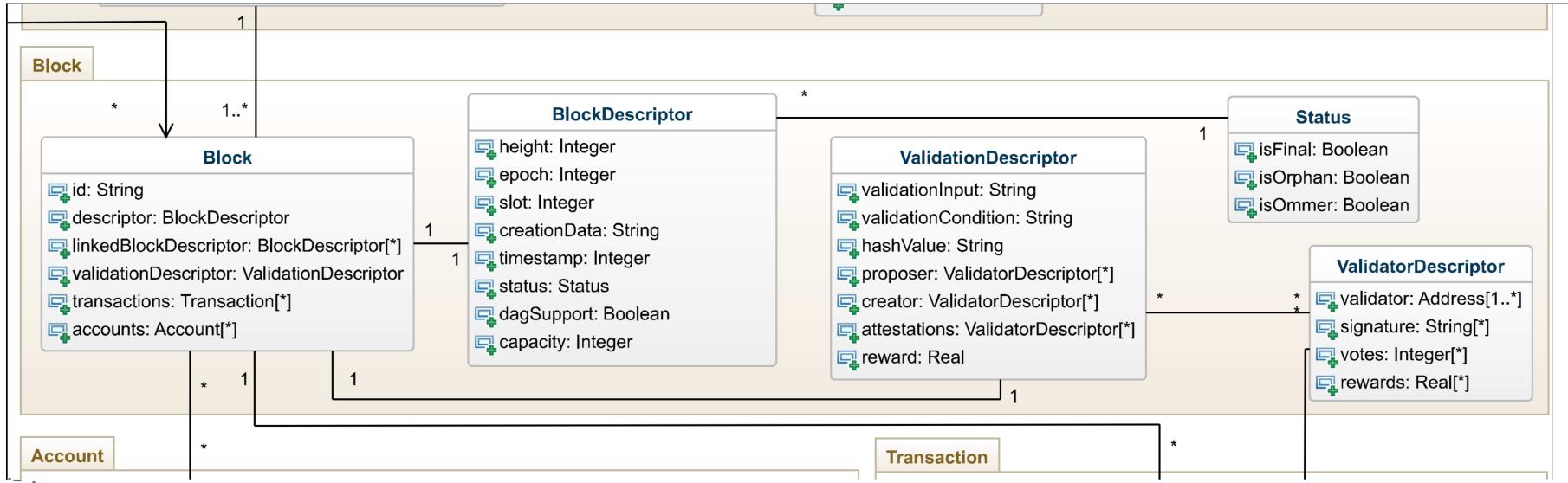
- Simultaneous access to multiple blockchains in individual query statements
- Utilization of the properties provided by blockchains

## Related Publication:

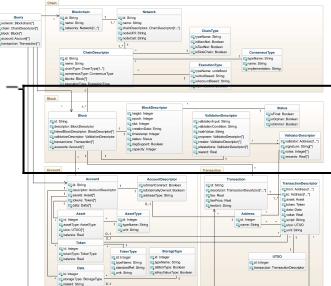
Härer, Felix (2022): **Towards Interoperability of Open and Permissionless Blockchains: A Cross-Chain Query Language**, in: Proceedings of the 2022 IEEE International Conference on E-Business Engineering (IEEE ICEBE 2022), October 14-16, 2022, Bournemouth, UK. [Preprint arXiv:2209.07224 \[cs.DC\]](https://arxiv.org/abs/2209.07224)

# CROSS-CHAIN QUERY LANGUAGE – DATA MODEL

Data model derived from the blockchain concepts



## Excerpt: Block Classes



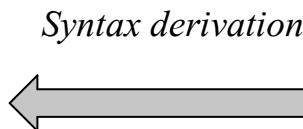
C.f. Figure 1

# CROSS-CHAIN QUERY LANGUAGE – SYNTAX

Syntax definition based on Query-Source-Filter blocks using data model classes

## Syntax

```
<QueryStatement> =  
  Q <AttrSpec> (, <AttrSpec>)*  
  S <SourceSpec> (, <SourceSpec>)*  
  [F <FilterSpec> (, <FilterSpec>)*];
```



## Example

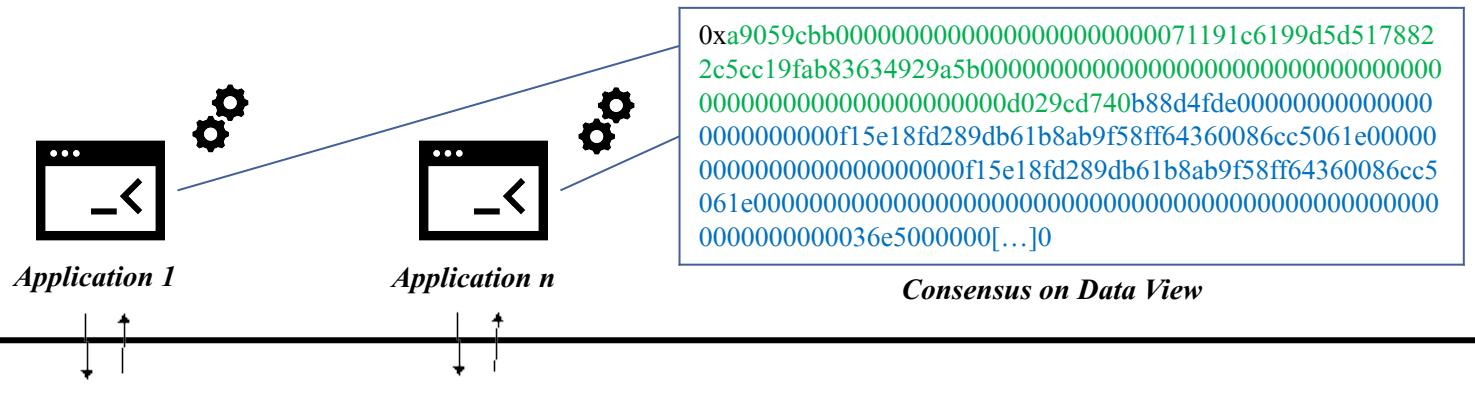
```
Q T.id, TDesc.value, TDesc.unit, TDesc.data  
S eth:main:1:Transaction.0xf50fc4bece6589655cc  
366ff2638de0e2ed61e01b500c138d5d3cd5450327334,  
avax:main:c:Transaction.0xb6b05f59ba6b69a082e6  
a8828d2afbf83a8847854fC56F3cC26a32e929104cef  
F TDesc.value == 0.0
```

## EBNF Grammar Specification

```
1  QueryStatement ::=  
2    QueryAttrClause  
3    SourceClause  
4    FilterClause? ";"  
5  
6  QueryAttrClause ::=  
7    'Q' AttrSpec (, AttrSpec)*  
8  SourceClause ::=  
9    'S' SourceSpec (, SourceSpec)*  
10 FilterClause ::=  
11   'F' FilterSpec (, FilterSpec)*  
12  
13 AttrSpec ::=  
14   CCQLClass '.' AttrName  
15 SourceSpec ::=  
16   BlockchainI ':' NetI ':' ChainDescI  
17   (':' ( BlockI | TxI | AccI ) )?  
18 FilterSpec ::=  
19   CCQLClass '.' AttrName ComparisonFunction IValue  
20  
21 CCQLClass ::=  
22   ChainPkgClass | BlockPkgClass | TxPkgClass | AccPkgClass  
23  
24 [...]
```

# CROSS-CHAIN QUERY LANGUAGE – APP. EXAMPLE

*Application  
Layer*



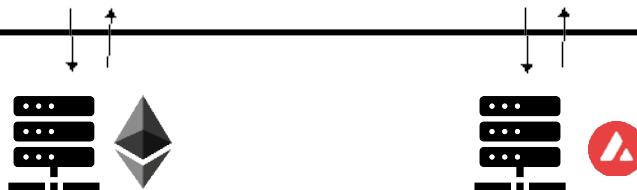
*Data Layer*

1:Transaction.id 1:TDesc.value 1:TDesc.unit  
0xf50fc4bece65890  
655cc366ff2638de  
0e2ed61e01b500c  
138d5d3cd545032  
7334

1:TDesc.data      2:Transaction.id 2:TDesc.value 2:TDesc.unit 2:TDesc.data  
0xa9059cbb00000000 0xb6b05f59ba6b6 0 AVAX 0xb88d4fde0000000  
0000000000000000719a082e6a8828d2a  
191c6199d5d5178822 fbf83a8847854fc5  
c5cc19fab83634929a 6f3cc26a32e9291  
5b000000000000000004cef  
000000000000000000000000  
000000000000000000000000  
000d029cd740

1:TDesc.data      2:Transaction.id 2:TDesc.value 2:TDesc.unit 2:TDesc.data  
0xa9059cbb00000000 0xb6b05f59ba6b6 0 AVAX 0xb88d4fde0000000  
0000000000000000719a082e6a8828d2a  
191c6199d5d5178822 fbf83a8847854fc5  
c5cc19fab83634929a 6f3cc26a32e9291  
5b000000000000000004cef  
000000000000000000000000  
000000000000000000000000  
000d029cd740

*Physical  
Layer*



# CROSS-CHAIN QUERY LANGUAGE – DISCUSSION

Cross-chain query language with data model, syntax, processing architecture

- Homogeneous data access
- Simultaneous access to one or more blockchains
- Standardized queries abstract from blockchain implementations

→ Software applications gain a shared view on data, secured by blockchain properties

Härer, Felix (2022): **Towards Interoperability of Open and Permissionless Blockchains: A Cross-Chain Query Language**, in: Proceedings of the 2022 IEEE International Conference on E-Business Engineering (IEEE ICEBE 2022), October 14-16, 2022, Bournemouth, UK. [Preprint arXiv:2209.07224 \[cs.DC\]](https://arxiv.org/abs/2209.07224)

# INTEROPERABILITY BEYOND BLOCKCHAINS

## Application Level Interoperability

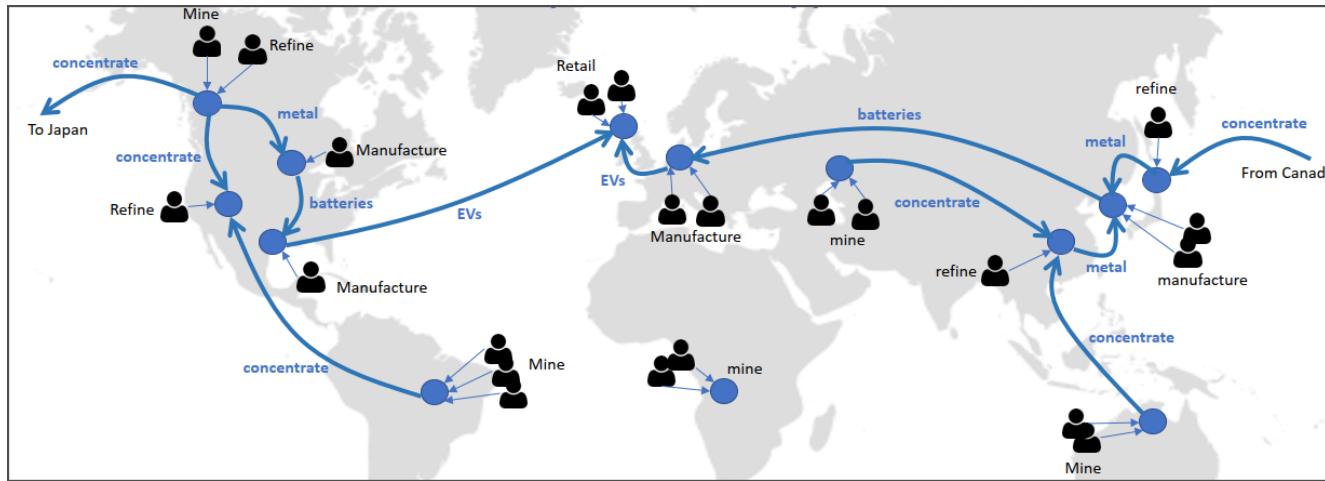
Interoperability of blockchains with, e.g.,

- Web and internet protocols
- IT architectures and the cloud
- Business Processes and Supply Chains

*Interoperability with real-world applications deployed today?*

# INTEROPERABILITY BEYOND BLOCKCHAINS

## *Interoperability with real-world applications deployed today?*



# Textile Supply Chain

# UPI Payments in India



UN/CEFACT,  
Capell

New York Times,  
01.03.2023

# INTEROPERABILITY BEYOND BLOCKCHAINS

## Verifiable Credentials

"A verifiable credential is a tamper-evident credential that has authorship that can be cryptographically verified. Verifiable credentials can be used to build verifiable presentations, which can also be cryptographically verified. The claims in a credential can be about different subjects."

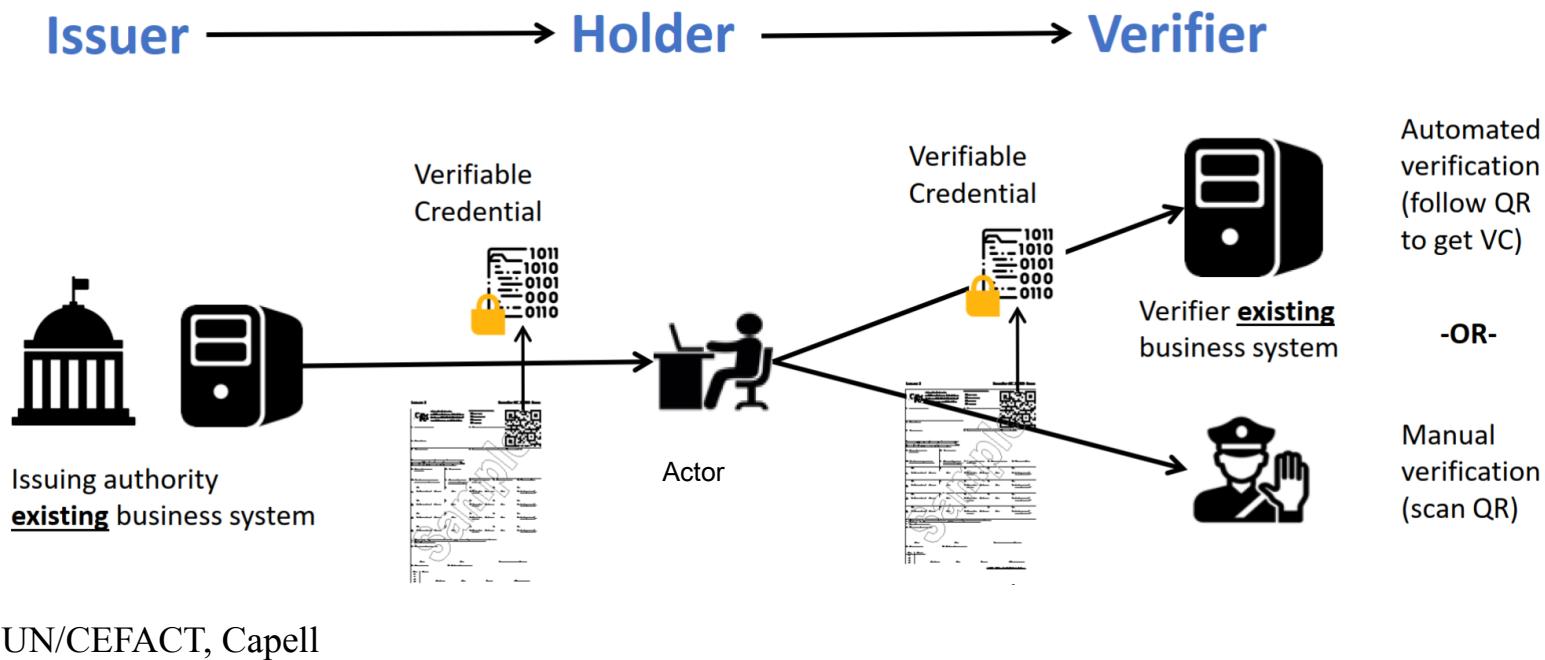


W3C Recommendation, Verifiable Credentials 1.1, 2022, VC Data Model

<https://www.w3.org/TR/vc-data-model/>

# INTEROPERABILITY BEYOND BLOCKCHAINS

## Verifiable Credentials - Application

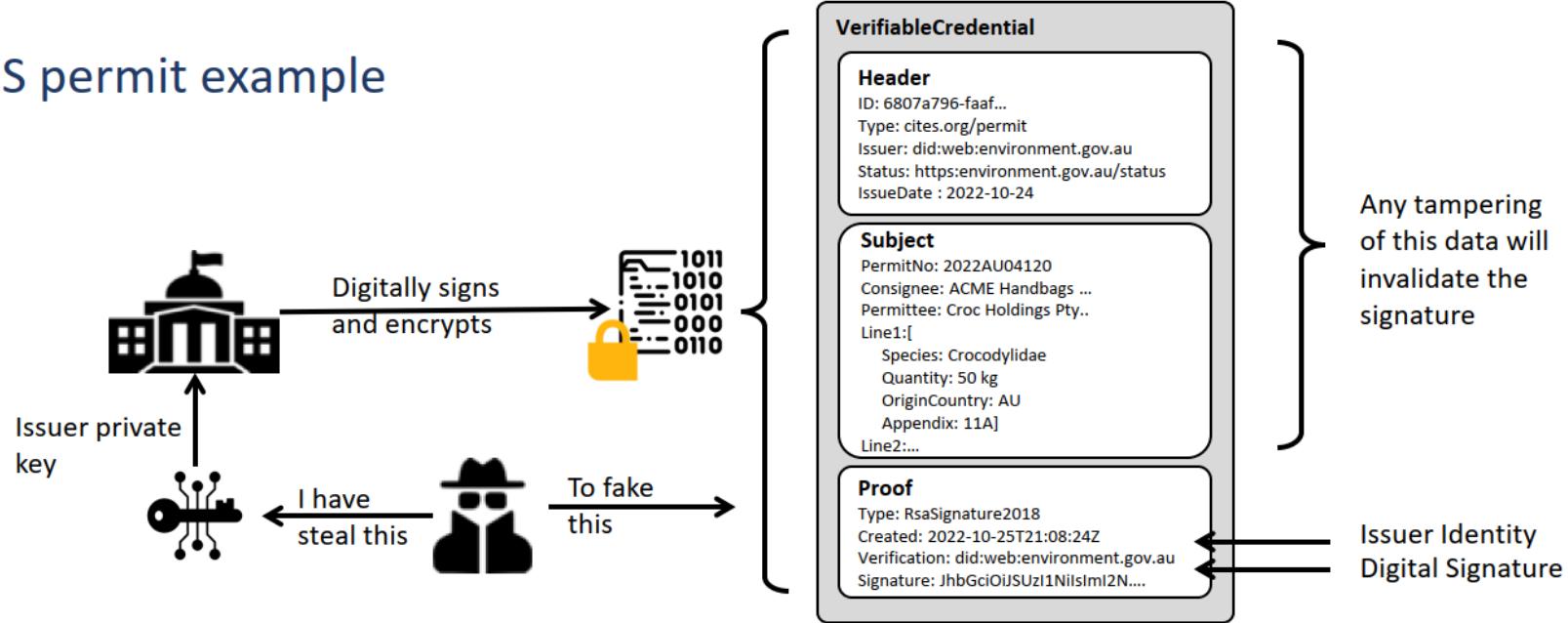


Verifiable by business systems and state authorities.

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## Verifiable Credentials - Application

### CITES permit example

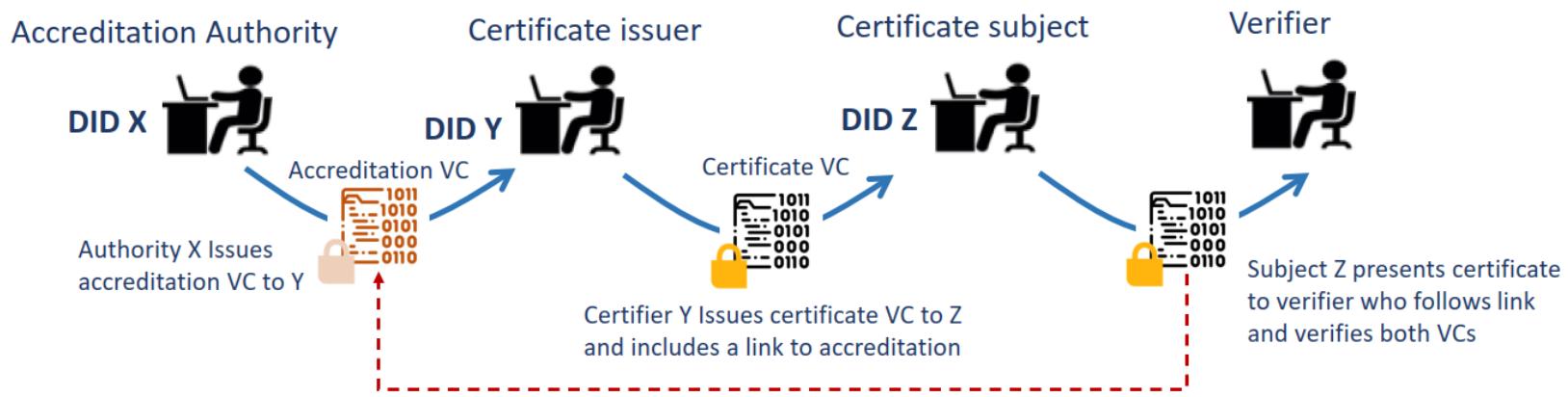


CITES:  
Convention on International Trade in  
Endangered Species of Wild Fauna  
and Flora (CITES)

UN/CEFACT, Capell

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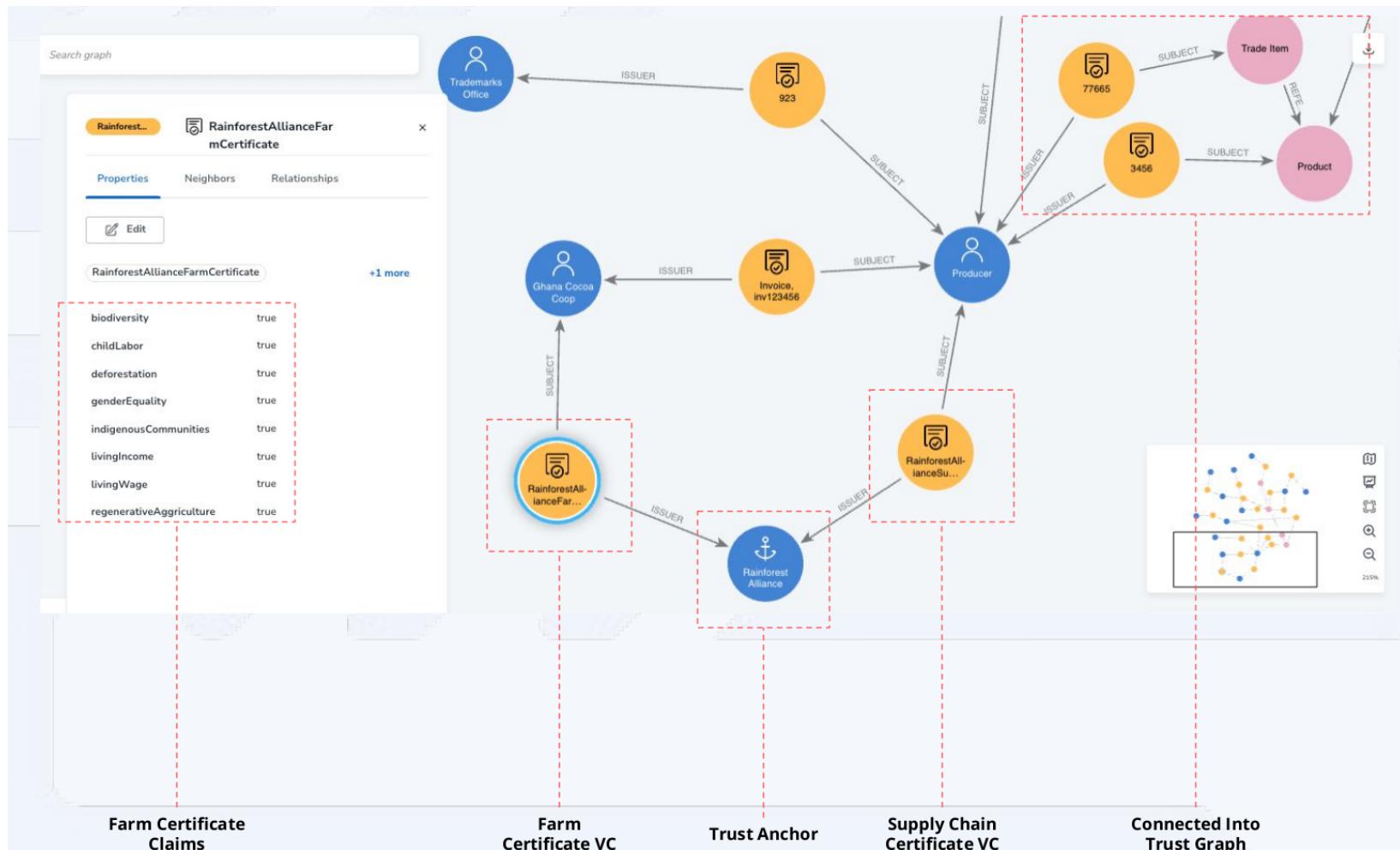
## Outlook - Decentralized Identifiers (DID) and Trust Graphs



UN/CEFACT, Capell

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## Outlook - Decentralized Identifiers (DID) and Trust Graphs



UN/CEFACT, Jespersen

# INTEROPERABILITY BEYOND BLOCKCHAINS

## Verifiable Credentials - Conclusion

- Portable and self-contained packet
- Secured using digital signature standards
- Can include a human rendering
- Compatible to existing systems

Scalable, Decentralized, Secure.



UPI Payments in India

New York Times,  
01.03.2023

## Support and Adoption

- Standardized by W3C
- UN/CEFACT recommendation to policymakers  
(40th UN/CEFACT Forum May 2023)

# BLOCKCHAIN FOR INFORMATION SYSTEMS

## Conclusion

**Verifiable Credentials, DID, UPI  
do not require blockchains.**

**We need standards on an application level.**

**We need systems compatible to real-world  
applications that are**

- open and permissionless,
- scalable,
- secure, and
- decentralized.



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***What is a blockchain?***



[unifr.ch/inf/digits](http://unifr.ch/inf/digits)

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