Blockchain Consensus Based on a Work: Thermodynamic and Quantum-inspired Interpretations for State Machine Architectures (Version 2)

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Abstract

This article aims to explore the affinity between thermodynamics and blockchain. An approach is presented, comparing the Proof-of-Work (PoW) process and an inverse Carnot cycle with the modeling of an abstract informational thermal machine. This opens up reflection on the nature of trust and the modeling of the state machine associated with blockchain consensus, then explores a possible convergence between blockchain consensus and quantum consensus. This article presents a theoretical approach to fundamental questions related to blockchain and has a pedagogical purpose. It concludes with proposals for industrial standardization objectives.

MAIN SECTIONS

1 Introduction

The question of the relationship between blockchain and thermodynamic is a subject that exists particularly in the case of work-based consensus. However, there are others possible approaches such as the affinity between money and thermodynamic [8] or mathematical formalisms from statistical thermodynamics in order for example to measure the level of decentralization (the level of disorder)[6] [5]. However it is less common to make a direct comparison between blockchain and thermodynamics. This is the approach of this document based on macroscopic thermodynamic (classical thermodynamic).

2 Fundamentals of the blockchain consensus cycle

2.1 Difference between validation and consensus

We often confuse consensus with validation. Validation is a kind a consensus but it is different. From an ideal point of view :

- Validation is reversible.
- Consensus is irreversible.

The purpose of this document is not to prove this assertion, it is rather to consider this as a starting hypothesis. A consensus is made by all validators. Consensus is stronger in this sens, but more difficult to achieve especially if there are many validators. Figure 1 shows the process of the PoW and where validation is and where is the consensus.There are two validation steps :

- The validation of the transaction. This is done by the miners just before putting this in the mempool.
- Bloc validation. It is carried out by miners who receive a bloc which has been broadcasted.

That complicates things with blockchain is that there is a technical part and an economic part. Thus miners are granted with rewards and with fees. It is two different things. Rewards reward the resolution of the puzzle. Fees are less important in value that rewards and are calculated by all the miners who place the transactions in the mempool. Secondly, the miner who solves the puzzle obtains the sum of all the fees associated with each transactions individually [7]. Fees are based on the size of the transaction and not the value of the transaction. However the fee is not the reward of the validation task. It is as if the validators are benevolent. However they can influence the place of the transaction in the mempool. The main object of the miners is in principle to solve the puzzle. This concept of consensus is ideal. In practice some miners works on solving the challenge for one bloc and the others for another block. They are not all working on the same puzzle. I use the term independent validation rather than just validation. For example, there may be groups of minors and this can pose a centralization problem. I use the term leader to refer to the miner who wins the puzzle. This may be surprising because the term leader is often used to refer to a consensus based on voting, and it seems strange that someone elected probabilistically could be considered a leader. It is nevertheless a leadership in the sense that he has a privileged role : that of creating the bloc.

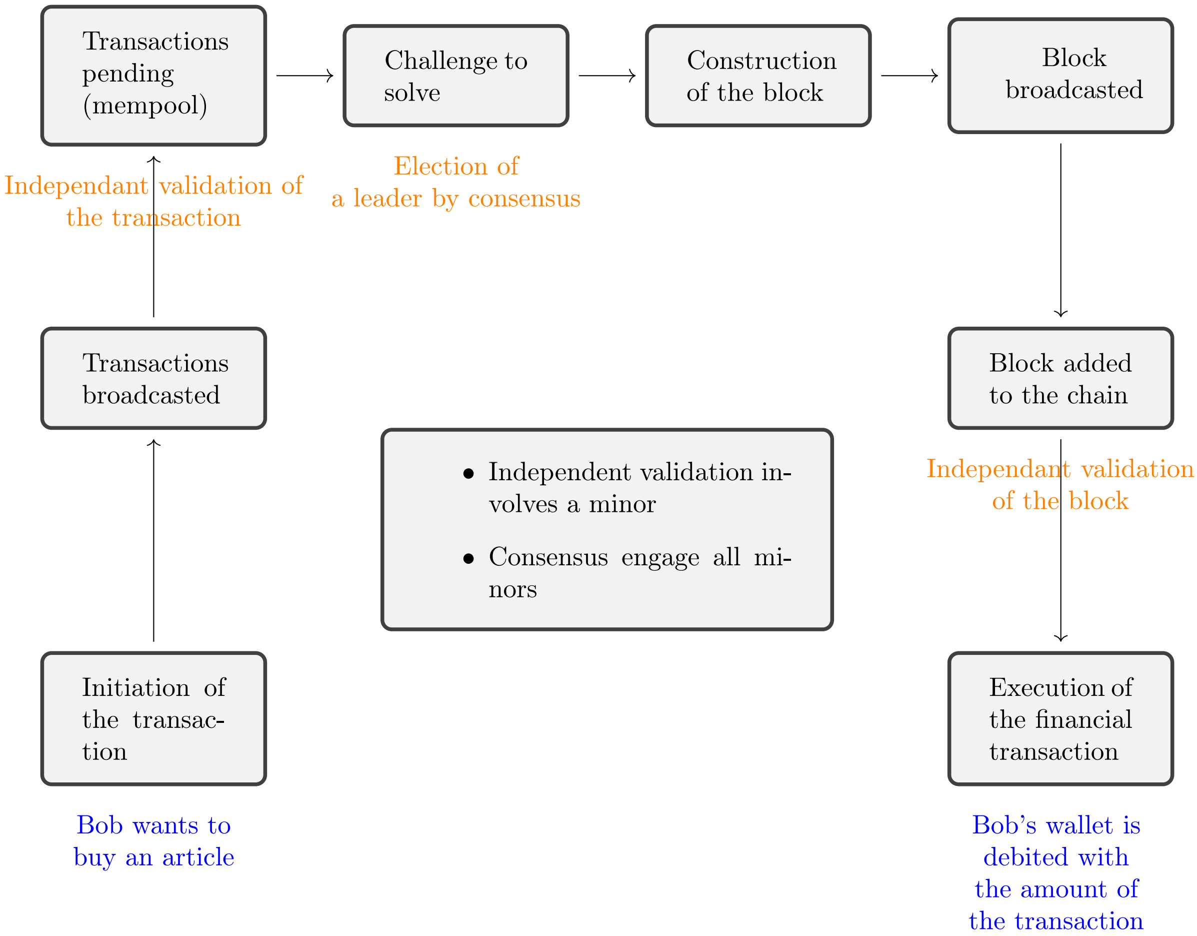

Figure 1: Respective place of validation and consensus in the proof of work process.

In the case of proof of work, here is the fundamental equation:

$$T_B = \frac{D}{H} \tag{1}$$

Where:

T_B = Blocktime
D = Difficulty
H = Hash rate

The notation used for the hash rate H is intended to differentiate it from Planck's constant h. One way to interpret the formula is to say that blocktime is the effect of difficulty given hashing speed. It should be noted that in the case of blockchain, the value of blocktime is a fundamental parameter. Its value is constant. In thermodynamics, there are irreversibilities. Typical irreversibility is energy loss due to the floors. It is irreversible because this energy is lost in the form of the Joule effect, and it is dispersed outside the system. This is why it is irreversible : the energy lost by friction is not recovered by the system. With proof of work, we consider that the energy used during the proof of work process is simply wasted. It is why I consider it irreversible. We can define now two properties of the consensus *when it is ideal* :

- A very large quantity of miners must be involved
- The energy must be wasted in useless work

Note that it is the opposite of thermodynamic where we define an ideal cycle when there is no irreversibilities. The ideal case does not mean that losing energy is the goal. It is perhaps preferable to have energy spent usefully (PoUW) for reasons of energy cost. The term ideal means only that the consensus is in its strong sense, in the sense of irreversible because the energy is lost for the system. The notion of system needs to be explored further because it involves the limits between the blockchain and the outside world. This is beyond the scope of this document.

2.2 First approach to the comparison between PoW and thermodynamics

We have seen that the PoW process has two different stages : validation and consensus, and that the two are different in their properties. We go further by saying that validation and consensus are associated with two opposite cycle : the direct cycle and the reverse cycle. It is shown in the table 1 :

Table 1: THERMODYNAMIC DIRECTION VS. PoW Process

#	THERMODYNAMIC CYCLE	PoW PROCESS
1	Direct Cycle (Engine)	Validation
2	Reverse Cycle (Refrig.)	Consensus

This means that there are two views of the blockchain cycle, whether we take it in reverse or direct direction. In my previous document [3] I talked about the blockchain engine. It is the direct direction. However I have not explored the reverse operation. This is the objective of this document concerning the thermodynamic part.

3 Thermodynamic description of the blockchain cycle

3.1 General description of the cycle in refrigerator (or heat pump) mode

This document was prepared in the search for a macroscopic and concrete approach of thermodynamic, in particular with the help of educational book [11]. For example the interpretation of the entropy parameter is macroscopic. What happens in the opposite direction ? The particularity is that the cycle does not provide motor work as in the Carnot cycle, but it is necessary to provide energy from the outside to compress the gas. The interest is that this creates energy in a direction opposite to that given by the second law of thermodynamics. The heat is not transmitted to the cold source, but to the hot source. for example in the case of the heat pump, the heat is taken from the cold outside and brought inside the warm house. This general cycle can be represented in the following diagram:

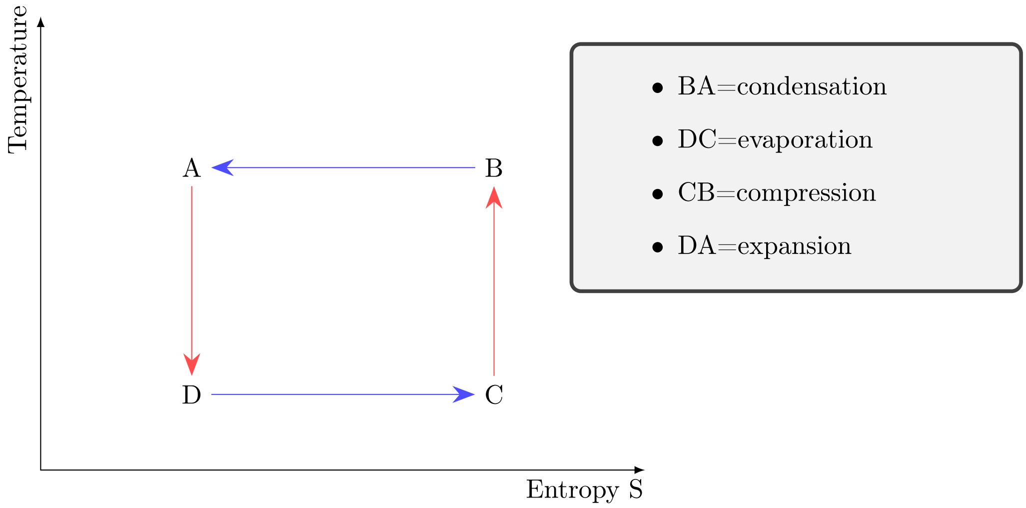

Figure 2: Reverse ideal Carnot cycle.

Avec :

$$\Delta S = \frac{\Delta Q}{T} \tag{2}$$

Where :

ΔS = Variation of entropy
ΔQ = Variation of heat
T = Temperature

Entropy is the effect of energy variation as a function of temperature. I would like to point out that this is an ideal cycle. This neglects irreversibilities.

3.2 Nakamoto refrigerator: reverse ideal blockchain cycle

In the figure below we are not talking about a Carnot cycle but a Blockchain cycle.

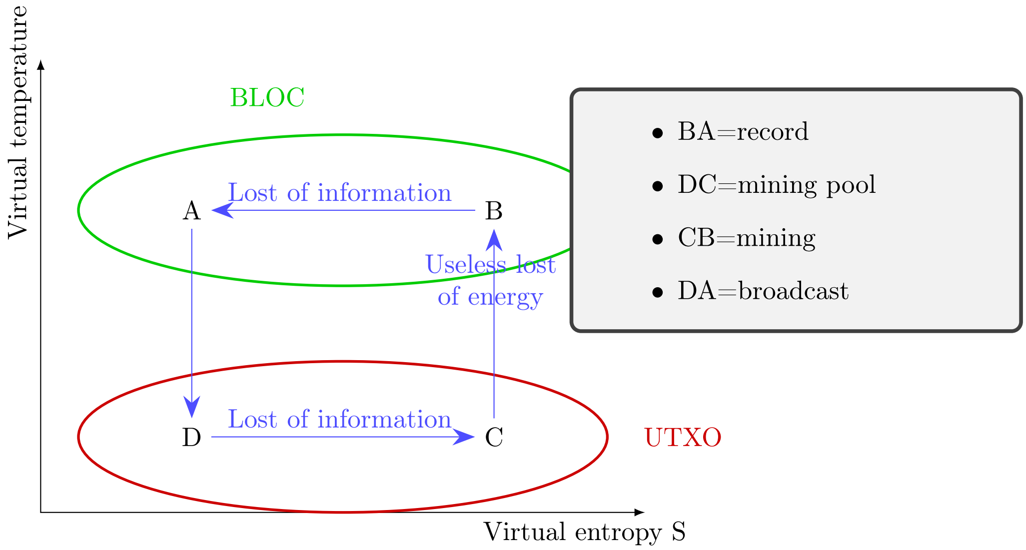

Figure 3: Reverse ideal blockchain cycle

In blue and red are indicated the losses of information and energy. There is the UTXO and block indication because what is at stake is the data structure: the steps involved are the network part and the data structure. This will be important later in the section relating to architecture. This is summarized in the table 2:

Table 2: REVERSE CARNOT VS. PoW PROCESS

#	REVERSE CARNOT CYCLE	PoW PROCESS
1	Compression	Mining (Hash)
2	Condensation	Record (Block)
3	Expansion	Broadcast
4	Evaporation	Mining Pool

The energy consumed by the blockchain is roughly comparable (in the idea) to the work required to operate the pump by an external motor.

I do not interpret entropy microscopically but macroscopically as the effect of the influence of heat transfer (influence of T). For example if it's cold and I get a small amount of heat from outside I will feel it a lot.

We complete with this fundamental point linked to the trust : where is the trust ? *It is in the first place the irreversibility that creates trust.*

Table 3: Levels of Trust

	Property	Trust level
1	Irreversibility	Strong
2	Ordering	Average
3	Date	Weak

Do not confuse ideal blockchain and ideal consensus.

- The ideal blockchain is the stable blockchain, in the sense of control theory (resistant to forks): this is a desired objective.
- The ideal consensus generates irreversibility: it may be desired or less depending on the case, for example for questions of energy consumption.

4 Blockchain from a state machine perspective

4.1 Why do we speak of a state machine for blockchain ?

State machines have fallen out of fashion since the invention of the theoretical model of the Turing machine and the development of today's computers, and state machines are generally associated with a simple device such as a drinks dispenser. The Ethereum blockchain offers a complete Turing environment at the application level. However, at the network level, regarding the transaction, the blockchain model of computation is that of an infinite probabilistic state machine.

4.2 First possibility : state composed of events

One possibility is to associate a state with all events. This includes event results such as data stored in memory [1]. It is a rather informational vision : information exists because it is the consequence of events.

4.3 Second possibility : state in the form of a persistant log (state machine replication)

It is the formalism introduced by the Paxos consensus algorithm and its improvement Raft which introduces a persistent log [1]. The log is the state of the state machine. In this case, updating the log with a new command is the state transition function and this process is called state machine replication. It is a formalism applicable to all consensus mechanisms but in particular to the Byzantine agreement from which it comes. If we translate this to PoW, blockchain validation can be seen as the transition function of blockchain [1] The problem with the Byzantine agreement is that trust is based on the guarantee of ordering and we have seen that this is a lower level of trust than the trust created by irreversibility.

4.4 Third possibility : state in the form of list of UTXO

What is the mechanism of UTXO (Unspent transaction output) ? This notion is not intuitive at first glance. It is used with some blockchains (like Bitcoin) to describe the state of the wallet. For example, if the wallet balance is 50 bitcoins, UTXO describe the contents not based on the balance but based on the list of possible outputs. For example Alice will send 20 bitcoins to Bob and there will be two UTXOs: the one composed of 20 bitcoins which will be sent to bob and a second UTXO of 30 bitcoins that Alice will send to herself (the sum being equal to 50) What is interesting with the UTXO is that it describes elementary units of transactions not yet carried out: it describes potentialities. From this perspective, the state could be defined as the list of UTXOs [10].

4.5 The shift : state as physical storage

In thermodynamics, a substance can have different states. For example, water can be in a solid, liquid or gaseous state: there are three possibilities. This corresponds to different organizations of matter. In information theory, there can be different types of information organization. There are two information structures:

- The *mempool* composed of all UTXOs: this is the potentiality
- The block

There is an affinity between consensus and the structure of information: how information is stored and the consensus process. *The description of the state machine will not mix transaction and consensus but storage type and consensus.* We now have the elements that will allow us to create the Petri net diagram.

4.6 Affinity with the concept of state in quantum physics

In quantum mechanics, a state of a system is all the information contained in the system at a given time. Therefore, the affinity is evident.

However, the notion of consensus relates to a very different nature of things. For example, consensus algorithms for blockchain are classified as deterministic or probabilistic. However, in quantum mechanics, consensus is associated with the mechanism of entanglement. Two entangled particles are correlated instantaneously: the algorithm that leads to consensus cannot be classified as deterministic or probabilistic because the phenomenon is instantaneous. Classical consensus, such as the Byzantine agreement, has had to coexist with a probabilistic approach brought about by Bitcoin and proof of work. We will also have to "deal with" quantum consensus.

4.7 Description of the Petri net associated with the consensus process

The purpose of Figure 4 is to combine notions linked to the consensus process with others linked to the mode of storage in a Petri net.

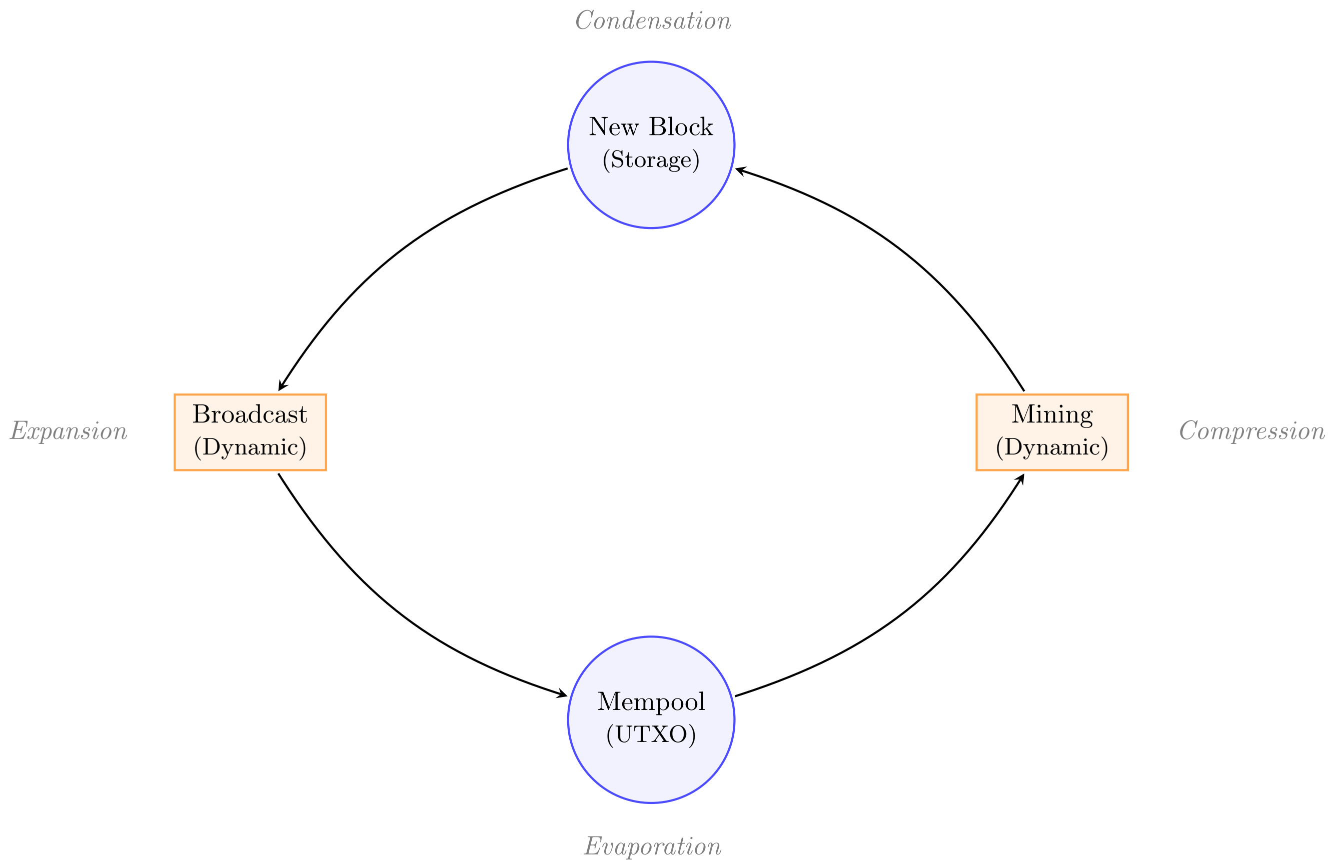

Figure 4: 'Mining' and 'Broadcast' act as transitions between the fluid state of the Mempool and the condensed state of the Storage (Block)

5 Dissipative cascade of the PoW

5.1 Simple case of a refrigerator

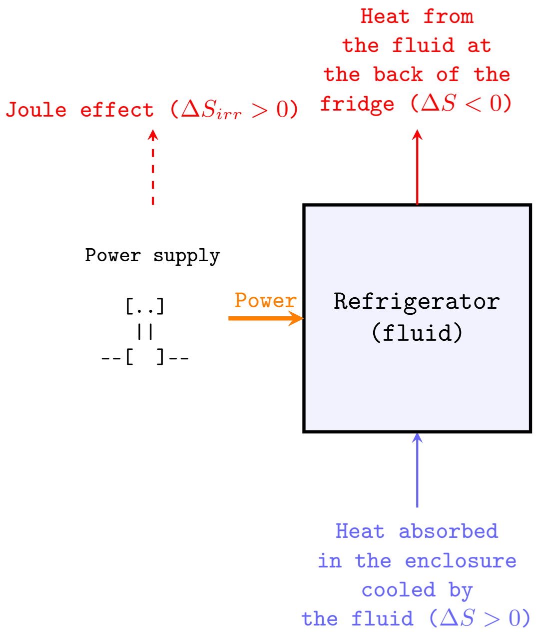

Figure 5: Thermodynamic model: Refrigerator and its power supply

5.2 Case of proof of work

First, it's important to understand that in classical thermodynamics, the operation of an engine or a heat pump is described based on a real device. For example, in the case of a heat engine, the driving force is created by a piston, which is indeed real. Discussing the Carnot cycle, whether in terms of a physical engine or its inverse, for a blockchain involves an effort at abstraction and imagining that virtual heat exchanges exist. However, the concept of entropy can be illustrated by basing it on the creation or decrease of order within the system. The concept is then more informational. However, the ambition here is to represent *an abstract machine*. The purpose of this machine is not to create an environment for executing a smart contract, as on Ethereum, but to achieve consensus. In a refrigerator, a compression mechanism heats the gas. Cold is taken from the cold environment: the inside of the refrigerator, and heat is added to the warm environment: the back of the refrigerator. By analogy, we can speak of logical compression to express the process of moving from a disordered environment to a less disordered one.

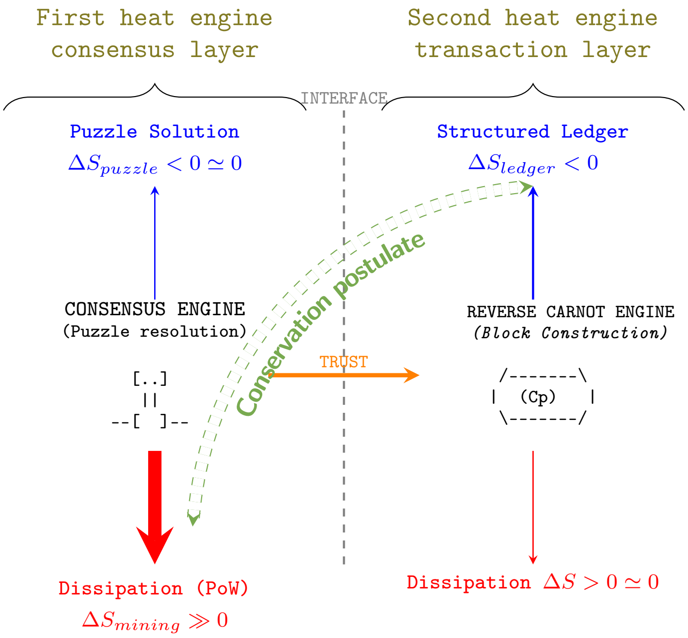

Figure 6: Dissipative cascade of the Pow: the solution to the puzzle (consensus) validates the right to operate the Carnot cycle (Transaction). It is a cascade of heat engines.

Consensus dissipates energy to solve a probabilistic puzzle ($\Delta S_{puzzle} < 0$), generating a flow of 'Trust'. This flow, in turn, powers a transactional inverse Carnot engine that transforms the chaos of raw data into an immutable, ordered ledger ($\Delta S_{ledger} < 0$). I posit that the blockchain system is a two-stage heat engine. The total entropy balance (ΔS_{tot}) can be written as the coupling of two opposing terms:

$$\Delta S_{tot} = \underbrace{\Delta S_{mining}} > 0 + \underbrace{\Delta S_{ledger}}_{<0} \tag{3}$$

Trust emerges when the system reaches an equilibrium point where the "Virtual Mass" created by ΔS_{trust} becomes greater than the thermal volatility of the network. We no longer live in the "sauna" of probabilities (gaseous states), but in the solidity of the ledger (crystalline state). Algorithmic work performs a dual negentropic mission: on the one hand, it reduces the uncertainty associated with validation (solving the cryptographic puzzle), and on the other hand, it stabilizes the order of transactions in the final data structure. Regarding the consensus engine, in the logic presented here, despite appearances, it also operates in a refrigerator mode: The PoW dissipates a great deal of heat, so we don't think it has a refrigerator function: the dissipated heat exists because the system needs energy to function, but we start from a disordered state—the puzzle to be solved—to an ordered state—its solution.

5.3 Contribution of statistical thermodynamics

We must distinguish between two perspectives:

- In the **classical** case,

$$\Delta S = \frac{\delta Q}{T}$$

  This expresses *how* entropy is exchanged within a thermodynamic cycle involving heat Q and temperature T.

- In the **statistical** case, we use the Boltzmann formula:

$$S = k_B \ln \Omega$$

where Ω represents the number of microstates. This expresses *what* entropy is: the measure of the possible microscopic configurations of the system.

As the number of possible combinations increases (related, for instance, to the nonce size), the entropy of the system rises accordingly. This demonstrates that statistical entropy and PoW difficulty are fundamentally linked, a relationship we will explore in the following sections.

5.4 Relationship between difficulty and logical temperature T_{log}

We know that: $\Delta S = \frac{\Delta Q}{T}$ and that $\Delta S = D$, so for ΔQ we get:

$$\boxed{D \propto \frac{1}{T}} \tag{4}$$

T_{log} is a parameter related to the trust and, for a given ΔQ, inversely proportional to the difficulty D. This is easily understood if we assume that the difficulty is proportional to the entropy.

5.5 Expression of the logical heat Q_{log} for PoW

It is inspired by the method used by Heisenberg in 1925, who used formulations from classical physics but introduced the quantization condition rather than directly seeking a quantum formulation. The idea here is to express what we have at the output of our blockchain appliance. In the case of a real refrigerator, this would be the logical heat produced at the back of the refrigerator. According to the classical formulation: $\Delta S = \frac{\Delta Q}{T} \Rightarrow \Delta Q = \Delta S.T$ However, we know that statistical thermodynamics gives us a microscopic view of the phenomenon, which allows us to understand that entropy is proportional to difficulty:

$$\Delta S \sim D$$

. We will therefore introduce this condition into the classical formula:

$$\Delta Q_{log} = D.T_{log}$$

Note that here we are moving away from the real machine. We use the abbreviation $_log$ to signify that we are not talking about physical quantities but logical ones.

$$T_B = \frac{D}{H} \Rightarrow \Delta Q_{log} = T_B.H.T_{log} \tag{5}$$

Where:

T_B = Blocktime
H = Has rate
T_{log} = Temperature
ΔQ_{log} = Logical Heat

Please note that this is not an analogy but what I would call a *hybridization*: a blend of physical and digital.

5.6 How to evaluate the order created in the register?

```
                          LOGICAL COMPRESSION

[ MEMPOOL ]          [ COMPRESSION ]            [ BLOCK N ]
(Chaos/Gas)            (Consensus)             (Order/Solid)

   Tx.C                    |||||                .---------.
Tx.A   Tx.B   ===>       | PISTON |     ===>    | Tx.A | Tx.B |
   Tx.D                    |||||                | Tx.C | Tx.D |
                           vvvvv                '----[ #H ]--'

 S = High                Work (W)               S = Low (0)
```

Figure 7: Representation of the compression cycle within the abstract machine..

Blocks are generally represented as linked together by a connection, and this creates the rigidity of the chain. One might place the creation of order here, but it's the opposite: each block is linked to a transaction, and a transaction is a self-contained environment. For example, a smart contract starts at the beginning of the transaction and ends at the end, the execution of the smart contract ending with the completion of the transaction. Thus, the notion of order creation is not easy to grasp, and in reality, it is the separation rather than the connection that defines this order. We must think not in terms of blocks but of transactions: a state is not represented by a block but by the transition between two blocks: the transaction.

5.7 A review of the concept of entropy and an interpretation of its parameters

5.7.1 Changing perspective on entropy

The main problem is not defining the parameters of the abstract machine, but interpreting them. It is necessary to change our perspective on entropy. Indeed, the microscopic view of entropy leads to a near consensus that entropy measures the degree of disorder in a system. However, here we are not trying to do microscopic thermodynamics, but rather to create a bridge between blockchain and quantum mechanics. In this document, we have chosen to start from the classical view of entropy.

5.7.2 Case of kinematics

In kinematics, velocity is a quantity that measures, for a given motion, the ratio of the distance traveled to the elapsed time. Average speed is defined as: average speed of the journey = distance traveled / travel time, or:

$$t = \frac{d}{v}$$

This can be interpreted as follows: time is the effect of the change in distance due to speed. It's as if time t lags behind the movement. Note that speed is always measured over an interval, for example, $t_2 - t_1$.

5.7.3 Case of classical thermodynamics

If, by analogy, we take:

$$T = \frac{\Delta Q}{\Delta S}$$

We can say in a classical thermodynamic framework that the temperature is *the effect* of the heat change, taking into account the entropy change. I posit that this effect has a derived nature *from an action* (as generally expressed in Joules.s). Thus, if T_{log} is related to the Action, and ΔS_{ledger} is a transition (dimensionless or in bits), then the product $T_{log} \cdot \Delta S_{ledger}$ does indeed preserve the dimension of energy (or heat).

5.8 Approach by state transitions

We can analyze the blockchain through two distinct lenses:

- **Quantitative:** The change in logical heat (ΔQ_{log}), which is fundamentally linked to the physical space and resources.
- **Qualitative:** The change in ledger entropy (ΔS_{ledger}), which expresses the transition between two states.

In this framework, the logical temperature (T) acts as an effect rather than a cause. This transition-based perspective is where our model converges with **quantum formalism**, specifically Heisenberg's 1925 approach focusing on energy transitions rather than static states.

From Entropy to Logical Mass

I previously held the view that ΔS_{ledger} was the direct analogue of time, as entropy is often called "the arrow of time." However, I now propose a more refined interpretation:

1. **Time-Temperature Equivalence:** It is T (logical temperature) that more accurately represents the temporal evolution of the system.
2. **Logical Mass Definition:** I define the **logical mass** of the blockchain as the cumulative hash expenditure of the Proof of Work (PoW).

This shift from a purely thermodynamic view to a mass-energy perspective serves as a bridge toward the quantum mechanical sections of this document.

6 Is a path to quantum mechanics possible?

6.1 Problem statement

This is where we get into the problem: does a unifying scheme exist that integrates classical and quantum blockchain? In the case of quantum blockchain, there is no energy consumption related to Proof-of-Work (PoW). However, there is a quantum jump from the initial state of the two entangled particles to their final state. The entanglement property, although it does not consume energy related to work, nevertheless requires experimental conditions that have constraints. What happens to the architectural scheme in this case? The underlying issue is whether the abstract machine remains possible and is consistent with the one previously constructed.

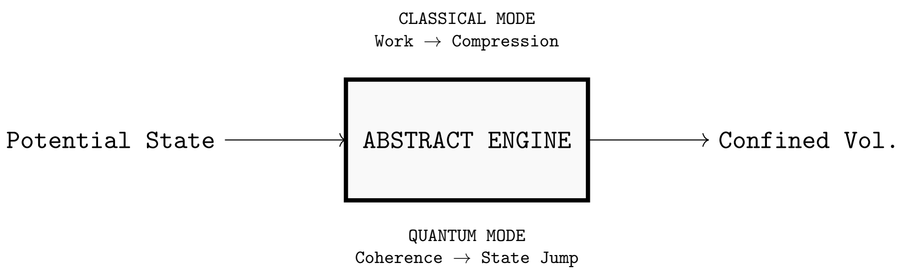

Figure 8: Unifying framework: The abstract machine as an architectural invariant between the classical and quantum regimes

6.2 Affinity between thermodynamics and quantum mechanics

This is a more fundamental section, but its purpose is to draw attention to the affinities between thermodynamics and quantum mechanics in order to prepare for the convergence between blockchain and quantum mechanics. We start with the macroscopic formula for entropy (**??**): $\delta S = \frac{\Delta Q}{T}$ This is the macroscopic interpretation: it represents a flow that we consider abstract between a given Q and a given T. We know the Planck-Einstein equation:

$$E = h\nu \tag{6}$$

(6) It is possible to assume that this formula has a thermodynamic structure. In this case, $h = \frac{E}{\nu}$, where h is Planck's constant and associated with it as a difficulty parameter. Thus, from (**??**) and (6), it is possible to deduce:

$$\boxed{h.\nu \approx \Delta S.T} \tag{7}$$

6.3 Summary table

h and ΔS are structural difficulties, while ν and T are linked to the system's temporal dynamics. This is an identification by analogy; however, in the case of an informational thermal cycle, we can speak of hybridization.

Table 4: Thermo vs. quantum synthesis

#	Parameter	Nature
1	h and dS	Structural difficulty
2	nu and T	Temporal dynamic

6.4 Proposal for industrial standardization objectives

6.4.1 Quantum playing field

This document is an exploratory research paper; however, it also aims to open avenues for standardization. To give an idea of the cultural gap to bridge, I quote Broeckaert and Verstraete [2] where it is stated that "if a problem can be transformed into a wave-like structure, then quantum mechanics handles it perfectly. Otherwise, it is simply not its playing field." While this expresses the common opinion, we are making the opposite assumption here for the case of consensus.

6.4.2 CEN-CENELEC Sector Forum "Energy Management" (SFEM) working group

The report of the SFEM (Sector Forum Energy Management – Energy Transition) blockchain working group [9] highlighted the need for a new reference architecture.

6.4.3 European standardization Rollout Plan

Among the European standardization actions is the ICT Standardization Rolling Plan [4]. Of the ten standardization actions mentioned, action 8 (energy efficiency) is the one that can most directly support the development and adoption of the quantum consensus algorithm, even though actions 1 and 4 play an important structural role. Here's why action 8 is crucial: it is the cornerstone of energy efficiency. Quantum consensus is distinguished by its near-zero energy cost (thanks to the reversibility of quantum gates).

6.4.4 Need for an inclusive architecture

It is important for standardization to plan cycles well in advance, keeping pace with technological innovation. For this reason, I propose that a reflection, particularly on architecture and governance, be initiated for an inclusive architecture that takes quantum consensus into account within a common frame of reference.

7 Conclusion

A quantum blockchain may not be a currency; a use case will need to be invented for it. However, the range of applications requiring a robust consensus process is broad. The example of Bitcoin, which showed that it was worth paying for the quality of consensus and that this was also a technical matter, was a pioneering experiment that draws attention to the challenges of consensus. Quantum consensus is probably a future scientific field, and its place within the consensus family is yet to be determined. The paradox is that Leslie Lamport began his career with special relativity, and this ultimately led him to quantum mechanics.

References

[1] Imran Bashir. *Blockchain Consensus: An Introduction to Classical, Blockchain, and Quantum Consensus Protocols*. Apress, 2022.

[2] Céline Broeckaert and Frank Verstraete. *Pourquoi personne ne comprend rien à la physique quantique (alors que tout le monde pourrait)*. Dunod, Paris, 2023. Traduit du néerlandais.

[3] Stéphane Caporali. Consensus, Cycle of Information and Blockchain Engine. 2023.

[4] European Commission. Rolling plan for ict standardisation 2025. `https://interoperable-europe.ec.europa.eu/collection/rolling-plan-ict-standardisation/rolling-plan-2025`, 2025. Accessed: 2026-01-23.

[5] Feng Liu, Hao-Yang Fan, and Jia-Yin Qi. Blockchain technology, cryptocurrency: Entropy-based perspective. *Entropy (Basel, Switzerland)*, 24(4):557–, 2022.

[6] Sishan Long, Soumya Basu, and Emin Gün Sirer. Measuring Miner Decentralization in Proof-of-Work Blockchains, 2022.

[7] Antonopoulos Andreas M. and Andreas M. Antonopoulos. *Mastering Bitcoin : programming the open blockchain / Andreas M. Antonopoulos.* O'Reilly, Beijing Boston Farnham Sebastopol [etc, 2nd edition (2017) edition, 2017.

[8] Pierre Noizat. Bitcoin et thermodynamique. https://e-ducat.fr/2020-06-26-bitcoin-et-thermodynamique/, June 2020. (Accessed on 04/13/2024).

[9] SFEM WG Blockchain DLT. Final report of the sector forum energy management. Technical report, SNV (Swiss Association for Standardization), 2021. Available at: https://www.snv.ch/files/content/Dokumente/Div.%20Dokumente%20Normung/SFEM_WG_Blockchain_DLT_final_report.pdf.

[10] Wenbing Zhao. *From traditional fault tolerance to blockchain.* Wiley-Scrivener, Hoboken, NJ, 2021.

[11] Çengel Yunus A., Boles Michael A., Lacroix Marcel, Godard François, Hallé Éric, Hudier Eric, Yunus A. Çengel, Godard François, Hallé Éric, and Hudier Eric. *Thermodynamique : une approche pragmatique / Yunus A. Çengel, Michael A. Boles ; traduction et adaptation française de Marcel Lacroix,... ; réviseurs scientifiques François Godard,... Stéphane Hallé,... Eric Hudier,...* Sciences de l'ingénieur. De Boeck, Louvain-la-Neuve, 2e édition edition, 2014.