

The CAP Theorem

Availability, Consistency, Failure in Distributed Systems

Distributed Systems

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- 1 Availability, Consistency, Failure
- 2 CAP at a Glance
- 3 A Brief Detour: Pokémon Go
- 4 Back to CAP: Some Proof
- 5 Building on CAP
- 6 Conclusion



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(Hiding) Failure in Distributed Systems

- being able to **keep on providing services in spite of failures** is supposed to be one of the main benefit of distributed systems over centralised ones [Friedman and Birman, 1996]
- intuitive assumption: **distributed systems can be designed** so that if one component of the system fails – or, it becomes disconnected / partitioned – other components can replace it so as **to hide failures** from the outside world
 - or at least to reduce the (perceived) impact of failure



Failure & Availability

- when a system can hide (most of) its failures, it is basically (almost) *always working*
 - we say it is *highly available*
- basic questions in the design of distributed systems: *how much failure can a given system sustain before failure is noticed?*



Features

What do we expect from a (distributed) systems? [Gilbert and Lynch, 2012]

- we would like them to behave *correctly*, to give correct replies when queried
 - to be **consistent** (Correttezza)
- we would like them to work, to make good things happen, to be *live*
 - to be **available** (Disponibilità)
- however, we know systems *can* actually experience power losses, crashes, network failures, message loss, malicious attacks, Byzantine failures, and so on
 - and be **unreliable** ^{inaffidabili} (Tolleranza alle Partizioni)

Tradeoff

Consistency: Garantisce che il dato restituito sia sempre corretto e aggiornato. Se non si può garantire, il sistema fallisce o blocca l'operazione.

Availability: Garantisce che il sistema risponda a una richiesta entro un tempo ragionevole. Il servizio continua a essere erogato (anche se con dati potenzialmente non aggiornati).

il CAP Theorem è la manifestazione più nota di un conflitto universale nell'informatica distribuita: la difficoltà di progettare un sistema che sia allo stesso tempo sempre corretto e sempre reattivo quando il caos (l'inaffidabilità della rete) colpisce.

The idea

“The CAP theorem is one example of a more general tradeoff between *safety* and *liveness* in *unreliable systems*” [Gilbert and Lynch, 2012]

Nei sistemi inaffidabili (cioè tutti i sistemi distribuiti nel mondo reale):

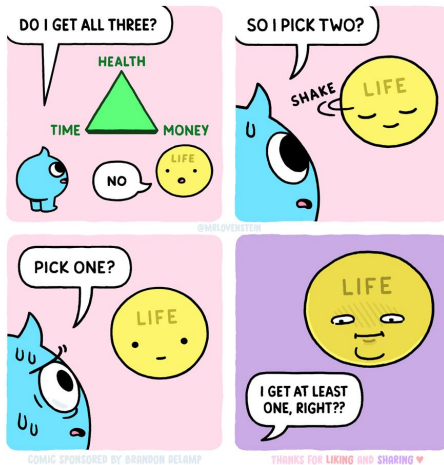
- Massimizzare la Safety (es. garantire una consistenza perfetta) spesso richiede di fermare il progresso del sistema (rendere il servizio non disponibile) quando si verifica un guasto o un'ambiguità, per evitare di prendere decisioni errate.
- Massimizzare la Liveness (es. garantire la massima disponibilità) spesso richiede di sacrificare la Safety (accettare che alcuni dati possano essere obsoleti o inconsistenti) per permettere al sistema di continuare a funzionare e rispondere.

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Informally I



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Informally II

Secondo il Teorema di CAP, è possibile fornire simultaneamente solo due delle tre seguenti proprietà nelle applicazioni distribuite: Consistenza (C), Disponibilità (A) e Tolleranza alle Partizioni (P).

In short^[Shim, 2012]

According to the CAP theorem, it is only possible to simultaneously provide any two of the three following properties in distributed applications: **consistency (C)**, **availability (A)**, and **partition tolerance (P)**.

Consistency: ogni lettura riceve il dato più recente scritto o un errore. Il sistema si comporta come se fosse un singolo nodo, garantendo un unico stato globale. Non permettere mai agli utenti di vedere dati vecchi o contraddittori.

Availability: ogni richiesta a un nodo non guasto riceve una risposta (non un errore o un timeout), garantendo che il servizio sia sempre operativo. Il sistema deve sempre rispondere, anche in caso di problemi.

Partition Tolerance: il sistema deve continuare a funzionare anche se si verifica una partizione di rete, ovvero una rottura della comunicazione tra gruppi di nodi (ad esempio, a causa di un guasto del cavo o di un server che isola una parte del sistema). Poiché le reti reali non sono mai perfette (il fallimento è inevitabile), la Tolleranza alle Partizioni (P) è considerata un requisito obbligatorio per quasi tutti i moderni sistemi distribuiti su larga scala.

Informally III

Less short^[Zhao, 2014]

The CAP theorem [...] states that it is impossible to satisfy all three of the following guarantees:

Consistency (C) the replicated data is always consistent with each other

Availability (A) the data is highly available to the users

Partition tolerance (P): the system can continue providing services to its users even when the network partitions
ci sono partizioni di rete



Original Theorem

First formulation by Eric A. Brewer^[Brewer, 2000]

A distributed database potentially features three desirable properties

- 1 Consistency
- 2 Availability
- 3 tolerance towards network Partition

According to the CAP theorem, any shared-data distributed system can have at most two of these three properties

<http://apice.unibo.it/xwiki/bin/view/Talk/BrewerPodc2000>

An Impossibility Result

- “we repent and renounce”
- ? ... yet, what is actually our sin?
- **distributed systems**, that's what it is.



Pick Up One... I

... and live with(out) that

- one might *forget about tolerance to network partition*, so to have consistency and availability
- one might *forget about consistency*, and live with a partition-tolerant and highly-available system
- one might *forget about availability*, and enjoy a system that is both consistent and tolerant to network partition

Pick Up One... II

Note

- the three properties are not exactly of the same sort, both technically and conceptually
 - consistency and availability range over a spectrum of options, whereas partition tolerance can somehow be seen more as an on/off feature
 - all of them are *desirable*, yet forfeiting partition tolerance is *not really an option* in real-world systems
 - particularly with pervasive systems in the IoT era, where *instability* (of the network) rules^[Grimm et al., 2004]
- long story short, CAP theorem most often forces us to *choose between availability and consistency*

Example: Location-based Games I

Location-based games

- *location-based services*^[Shekhar et al., 2016] use information about the position of a user / device to provide information, entertainment, security
- *location-based games* use player's location to evolve and progress the gameplay
 - e.g., BotFighters, GeoZombie^[Prandi et al., 2016], Ingress, Pokémon Go, Harry Potter: Wizards Unite, Minecraft Earth


Example: Location-based Games II

CAP in location-based games: partition tolerance

- since the architecture is built around the notion of millions of players roaming physical space *worldwide* with their mobile devices (and, playing through them), forfeiting **partition tolerance** is *not* an option
 - mobile devices are inherently *unstable* in their network connectivity
 - players are inherently *mobile*, and so they can move in and out of network coverage
 - players tend to concentrate in some areas, e.g., during special events
 - scalability is a multi-level issue: not just the number of players overall, but also the number of places they can be at, and the number of players at each place
 - e.g., costly disaster at the Chicago 2017 Pokémon Go Fest

Example: Location-based Games III

CAP in location-based games: consistency and availability

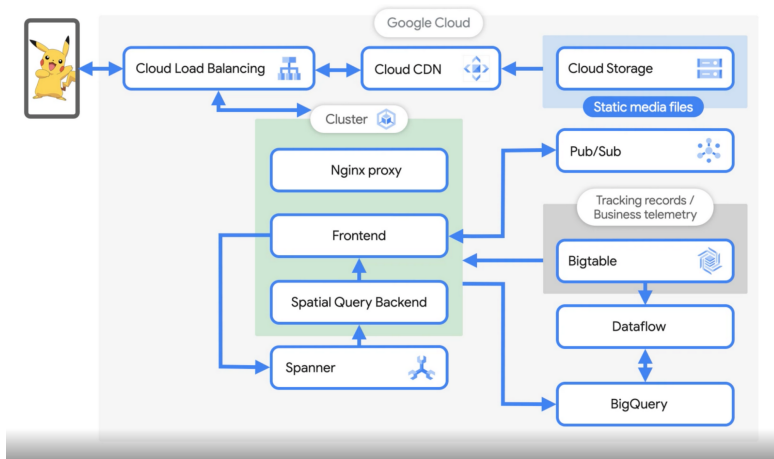
- **consistency** of the game data (goals, situation, achievements, ...) is essential to keep players going (and, into the game)
 - location-based games are usually built around logically-centralised architecture
 - using spatial replication in order to reduce user-perceived latency and improve scalability
 - when strong consistency is required, e.g., for in-game transactions, players might be forced to wait for the app servers to confirm the operation
 - by reaching a consistent state overall
- first (and usual) casualty: **availability**
 - the Spinning Wheel of Death 

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Catching a Pokémon on Google Cloud I



<https://cloud.google.com/blog/topics/developers-practitioners/how-pokémon-go-scales-millions-requests>

Catching a Pokémon on Google Cloud II

- ❶ when a player opens the Pokémon Go app, all static media are downloaded to his/her personal device
 - which are stored in Cloud Storage
 - **Cloud CDN (Content Network Delivery)** uses Google's global *edge network* to serve content closer to users
 - Cloud CDN works with the **Cloud Load Balancing** (actually, a load balancer) to *cache* and serve user content
- ❷ user requests are sent to **NGINX** reverse proxy
 - which sends this traffic to the Frontend game service
 - hosted on **Google Kubernetes Engine (GKE)**
- ❸ the Spatial Query Backend handle the location-based features
 - keeps a cache *sharded* by location
 - the cache and service decides which Pokémon is shown on the map, what gyms and PokéStops are around, which is the time zone, ...

Catching a Pokémon on Google Cloud III

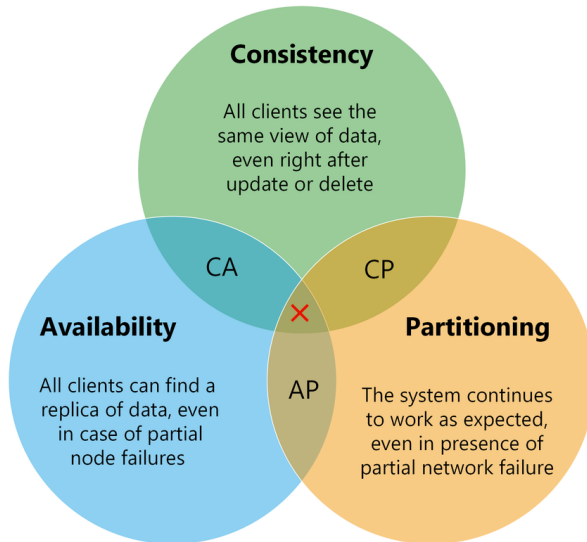
- 4 when a player catches a Pokémon, the Frontend (GKE) sends an event to **Google Spanner**
 - when the write request is completed, a response is sent back to the device
 - Spanner is *strongly consistent*
- 5 every player's actions is recorded in the **Bigtable** NoSQL database service
 - as a **Protobuf** representation
 - for logging and tracking data
 - also as a message to a **Pub/Sub** topic for the analysis pipeline
- 6 multiple players in the same geographical region are kept in sync by *determinism* of the Pokémon Go maps
 - even if multiple players are on different machines, but in the same physical location, all players' inputs would be the same
- 7 *all the servers are in sync with settings changes and event timings in order for all players to feel like they are part of a shared world*

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One Way to See CAP



From Brewer's Conjecture to CAP Theorem

Going formal

- Brewer's first results required some *proof*, possibly formal
- for a proof, a more precise formulation of the conjecture is required
- a proof was soon provided^[Gilbert and Lynch, 2002]
 - with some limitations
- then, several others followed
- first step for us to sketch a proof: defining the main concepts

Consistency, Availability, Network Partition I

Availability^[Gilbert and Lynch, 2002]

- “For a distributed system to be continuously **available**, every request received by a non-failing node in the system must result in a response”
- if the system is available, we got *responses*



Consistency, Availability, Network Partition II

Consistency^[Gilbert and Lynch, 2002]

- a **consistent** service is modelled as an *atomic data object*
- where
 - operations are totally ordered, and
 - each operation occurs in a single instant of time
- ! here, the meaning of *consistent* is unlike ACID properties, since it encompasses both A and C there
- among the many consequences, consistency implies that all *read* operations over a distributed shared memory occurring after a *write* operation completes must return the value of either this write operation or a later one
- if the system is consistent, we got *correct responses*

Consistency, Availability, Network Partition III

Network partition^[Gilbert and Lynch, 2002]

- “When a network is partitioned, all messages sent from nodes in one component of the partition to nodes in another component are lost”
- “And, any pattern of message loss can be modelled as a temporary partition separating the communicating nodes at the exact instant the message is lost”

In short, and roughly...

- if node A send a message to node B, the network is *partitioned* if the message does not make it to B
- *availability* is when B receives the message and responds
- *consistency* is when B response is correct

Theorem I

Three different sorts of systems

The proof is given for three sorts of network

- asynchronous network with message loss
- asynchronous network without message loss
- partially synchronous network with local clocks

For teaching purposes, we focus here on the *asynchronous model*, where

- there is no single clock
- nodes act based on local computation and message received

Theorem II

Theorem^[Gilbert and Lynch, 2002]

“It is impossible in the asynchronous network model to implement a read/write data object that guarantees the following properties:

- availability
- atomic consistency

in all fair executions (including those in which messages are lost)”



Proof^[Gilbert and Lynch, 2002] |

Assumptions

- atomicity, availability, and partition tolerance are all fulfilled
 - *proof by contradiction* attacks just that
- nodes in the network can be partitioned into two disjoint, non-empty sets G_1, G_2
- atomic object o has initial value v_0
 - o is expected to be consistent through G_1, G_2
- α_1 executes a single write $v_1 \neq v_0$ of o in G_1
 - α_1 is the only request in that time
 - during α_1 no message are received—from G_1 to G_2 , from G_2 to G_1
- no messages from G_1 are received in G_2
- α_2 executes a single read of o in G_2
 - during α_2 no message are received—from G_1 to G_2 , from G_2 to G_1

Proof^[Gilbert and Lynch, 2002] II

Q.E.D.

- due to availability, α_1 completes ($v_0 \rightarrow v_1$), and α_2 does, too
- executing α_1 and α_2 , G_2 just sees α_2 , and must return v_0
- this obviously violates consistency as defined above
 - which is basically a sort of atomic consistency



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What do we Make out of an Impossibility Result?

Should we stop distributing computational systems?

- in the same way we stopped using axiomatic systems after Gödel?^[Gödel, 1931]
 - of course we did *not*
- ! **negative results** just *set the boundaries*, and make us understand the very *limits of our reach*
- so that an impossibility result from computer science becomes a leverage for specific and effective computer engineering methods and practices

Switching Strategy based on Partition Tolerance

A very simple scheme

- Brewer himself later elaborated on his CAP theorem^[Brewer, 2012]
 - (i) when the network is partitioned, a distributed system should choose a tradeoff between consistency and availability
 - (ii) when there is no partition, a system can feature both consistency and availability



ACID vs. BASE I

Beyond ACID^[Fox et al., 1997]

- ACID (Atomicity, Consistency, Isolation, and Durability) semantics might be too strong
 - “The design space for network services can be partitioned according to the data semantics that each service demands. ”
 - “For other Internet services, however, the primary value to the user is not necessarily strong consistency or durability, but rather high availability of data”

ACID vs. BASE II

Towards BASE^[Fox et al., 1997]

- “Stale data can be temporarily tolerated as long as all copies of data *eventually* reach *consistency* after a short time”
- “*Soft state*, which can be generated at the expense of additional computation or file I/O, is exploited to improve performance; data is not durable”
- “*Approximate answers* (based on stale data or incomplete soft state) delivered quickly may be more valuable than exact answers”

BASE

- Basically Available
- Soft state
- Eventual consistency

Beyond BASE

Data consistency for Cloud^[Birman et al., 2012]

- most cloud services nowadays adopts BASE
 - e.g. eBay, Amazon DynamoDB
 - ! Amazon S3 allows for *strong read-after-write* consistency
 - ! Amazon DynamoDB writes are eventually consistent, reads too—but strongly-consistent reads can be configured (and, they are more costly)
- and try to mask inconsistencies from users
- steps ahead are leading to new models, based on, e.g., new data-consistency models
 - ! further details in the literature—at the end of the slides

Overall

CAP today^[Brewer, 2012]

The modern CAP goal should be to maximise combinations of consistency and availability that make sense for the specific application. Such an approach incorporates plans for operation during a partition and for recovery afterward, thus helping designers think about CAP beyond its historically perceived limitations



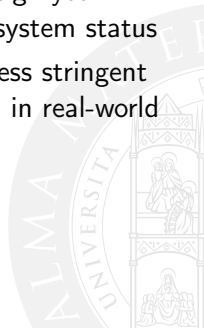
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Lessons Learnt

- in the design and development of distributed systems, we have typically to choose between a responsive system and a fully-consistent one, when network fails
- in any case, we can leverage on the CAP theorem to design your system with different features depending on the overall system status
- ACID is generally a thing to know and understand, yet less stringent models could be both theoretically and practically useful in real-world distributed systems—e.g., BASE



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