Spacetime-Entangled Networks (I)
Relativity and Observability of Stepwise Consensus

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Abstract—Consensus protocols can be an effective tool for synchronizing small amounts of data over small regions. We describe the concept and implementation of entangled links [1], applied to data transmission, using the framework of Promise Theory as a tool to help bring certainty to distributed consensus.

Entanglement describes co-dependent evolution of state. Networks formed by entanglement of agents keep certain promises: they deliver sequential messages, end-to-end, in order, and with atomic confirmation of delivery to both ends of the link. These properties can be used recursively to assure a hierarchy of conditional promises at any scale. This is a useful property where a consensus of state or ‘common knowledge’ is required. We intentionally straddle theory and implementation in this discussion.

I. INTRODUCTION

We describe the agents, promises, and assessments involved in making a multi-layer message-passing channel, using the property of entanglement. Entangled network links are a concept for transmitting data transactionally. They keep basic promises about message integrity. Their design principles can be applied recursively to build a transaction based hierarchy of communication, from the packet to the application level.

Entanglement networks, proposed by Borrill [1], promise to deliver sequential messages, end-to-end, in a path-independent invariant order, and with confirmation of delivery to both ends of the link. These are properties more usually associated with database transactions. While this may seem trivial over a point to point link, it is a useful low level property for building cases where a consensus of state, or common knowledge, is required. Some of the properties mentioned are available in any reliable message protocol (e.g. TCP), but in a form that may not be optimal [2]. In this work, we establish the hierarchy of constraints for keeping low level promises about reliable message propagation.

A. Entanglement

Entanglement is an information theoretic property [3], which means that several agents act inseparably, i.e. their outcomes are co-determined. In pair-entanglement, whatever is promised by one end of the link, depends on what is (or was) promised by the other end of the link in an absolute and causal manner, and vice versa. This constraint of mutual circularity (a form of semantic ‘deadlock’ in computer science) has eigenstates that admit strongly correlated or anti-correlated behaviours, and may be used to lock the endpoints into acting as a unit. Correlated behaviour allows communicating parties to keep in step. Anti-correlated behaviour allows the end points to distinguish their separate identities without ambiguity, so that input and output are expelled to the extrema of the link, away from the middle, where non-intentional noise sources could interfere. This suggests that the intentional management of boundary conditions alone could be used to modulate a state, and propagate a message, making the channel quasi-synchronous and quasi-deterministic. We shall explain the essence of these claims below.

If entanglement can be maintained, over successive promise-keeping exchanges, then, even as data are passed across the link, a kind of temporal integrity (stepwise ordered delivery without dropped packets) could be maintained. The scaling of the concept is the key to its applicability: our aim is to make it an irreducible promise, kept by an effectively irreducible link, acting as a single scaled agent [4], meaning that one end of a link cannot act without consequences for the other end. It is this irreducibility that one hopes to exploit in designing a mechanism for reliable communication at the most primitive level.

The paper has the following structure:

• We define the concepts and notations.
• We define senders, receivers, messages and packets.
• Messages and packet encodings are defined in some detail.
• Implementation of a link entanglement is shown.
• We assess some of the promises of entanglement relative to alternative technologies.

B. Motivation for a new delivery mechanism

Conventional link layer protocols are ‘unreliable’, meaning that they make no assurances of delivery [2], [5]. Higher level constructs, such as TCP re-construct reliability with acknowledgement circuits, but the application streaming abstraction limits one’s ability to reason about failures, and pushes recovery to the application layer: if a packet does not arrive within a certain time, one is not sure why or what to expect. Many failure modes in communication are related to infrastructure issues, which could reasonably be expected to self-repair. However, useful feedback is lacking at the infrastructure level, because the reliability circuitry is at too high a level. Our proposal here
is to push the feedback circuitry down the stack in a fundamental way.

In telephony, lower layer protocols like the ITU’s Public Network Signalling SS7 protocol, MTP layers 2 and 3 offer lower level reliability and recovery quite similar to the scheme described here [6]. Of the many others, we mention ATM [7], Virtual Synchrony [8], Distributed State Machine Replication [9], etc. However, these protocols work atop opportunistic signalling mechanisms, and lack the ability to say precisely when a packet was delivered, from one end to another, at each leg of a journey. This resilience properties have to be built top down, instead of bottom up, where they can have a more effective impact. If one cares to know when data were received, e.g. during financial transactions, or when parties knew certain facts within a chain of evidence, then both sides of a transfer can benefit from finer grained control over transactions, working together with a smarter automated infrastructure.

The key underlying limitation on predictability is the indeterminism of network communications, compared say to the relative determinism of communication of a motherboard PCI bus. We pose the question: could one construct the same level of deterministic trust on a cloud scale, as for a single motherboard computer bus. Scaling a set of deterministically reliable promises is a challenge that deserves serious consideration, especially in the context of ‘cloud’ or utility computing.

The infamous Fischer, Lynch and Patterson (FLP) result [10], which details how consensus is impossible in an asynchronous system if agents only might be unreliable, is one of the most discussed issues in system reliability. Consensus protocols [11]–[13] make a variety of promises concerning transactional ordering and versioning races. Entangled links, as described here, might be helpful in calibrating what data units consensus might profitably be applied to. One can engineer ‘observability controls’ into the approach, limiting or locking what observers can see at each moment. Endpoints recover synchronicity in communications by being exempted from low level details, and preventing contentious races from flapping data unnecessarily. Conceptually, by altering the way states change (or whimsically by redefining the way time is counted) at the communicating endpoints, the parties in a system could be prevented from seeing inconsistent states before clear promises can be made about their interpretation. The ‘management of moments’ might be applied at a number of levels. In this note, we focus on explaining the mechanism for general application.

C. Promises

What promises do agents need to make at each scale to claim such properties? Ordered delivery is not so much the issue: within an identifiable message, packets can and usually have to be numbered, so this is not a serious problem. However, for messages with disconnected origins, such as new and competing transactions to a bank account, asserted as impositions [14] rather than being promised by mutual arrangement, conflicts can arise, and there is uncertainty about when or whether packets were delivered. Packets that arise from independent sources and locations cannot be ordered meaningfully\(^1\) with respect to one another at the sources, since the sources have no calibrated causal alignment, rather it is important to know in what order they were accepted by an aggregator.

Causal co-dependence is the common theme in this work. Whatever the agents in a distributed system promise, they must promise it together, as an indivisible causal unit in order to keep in step with one another. That umbrella promise may be used to engineer a perception of determinism, and to place precise limits on what is meant by simultaneity inside the system. Ultimately, the goal is to be able to reason deterministically about states (with all the advantages that entails), rather than handing off responsibility to application level logic, which is already impaired by the uncertainty of the layers underneath.

This, then, is a reasonable foundation for certainty. Entanglement is not a transitive property, so wide area communications cannot assume the same promises as agents over a small scale, but one expects that approximations can be worked, by forwarding through trusted intermediaries, or the recursive application of the entanglement method. These methods could make particular sense in environments with physical assurances, like datacentres, and enclosed circuitry. At first glance, entangled links might not seem to contribute anything new in the field on networking, but the benefits can be expected to lie mainly in pursuit of the goal of ‘knowability’ in a characteristically space beset by uncertainties.

II. NOTATION AND CONFIGURATION

The idea of entangled links is quite simple, but turning the idea into a message passing channel involves a surprising number of details. In this section, we establish a language and notation for describing the parts of the system. The basic arrangement is shown in figure 1.

A. Cell agents

The independent locations of interest in a network (i.e. the promise theoretic intentional agents) are called cells. They are the originators (sources) and recipients (sinks) of messages in a system; e.g. they may be ‘servers’ in a datacentre, but they could also be virtual units of agency, such as an application container or a sensor. They must have a certain amount of memory for recording state, and buffering messages decomposed into packets (a message is defined to be a collection of

\(^1\)For some purposes one can approximately calibrate a set of timestamps by approximately synchronizing clocks through a single time source, assuming that they run at approximately the same rate, under approximately the same conditions, but this is liable to run into problems where the approximations fail.
packets). We denote them by $C_i$ (where $i = 1, 2, 3, \ldots$ runs over all cell agents). Cells can encapsulate any number of layers of entanglement in order to pass aggregations of atomic messages across aggregations of intermediate agents, hierarchically; however, we shall only illustrate the principles using two layers in this paper.

We begin, therefore, with the interaction of a single pair of cell agents, connected by a dedicated network channel. We label these $C_L$ and $C_R$ in their roles as ‘left’ and ‘right’ ends of a connection. These will variously play the roles of sender and receiver. The cell agents’ role in this discussion is to maintain state on the level of a message, and to preserve a memory of their own identity during the entanglement at the level of messages. They must also promise sufficient memory for message queues (buffers) of some length, for incoming and outgoing messages; no message can have meaning without memory to hold it, as an entity, in its entirety. These assumptions prove to be of central importance.

B. Network interface agents

Two nodes, which we may arbitrarily refer to as left $C_L$ and right $C_R$ communicate via a network channel whose endpoints are the network interfaces $N_L$ and $N_R$ respectively. Network interfaces are intermediary proxies for cells they attach to. They are promise-theoretic agents, since they make specific localizable promises. Interface agents are much simpler agents than cells, with only registers for sending and receiving single packets. Their capabilities determine the promises they can keep (and vice versa), they are one-to-one.$^3$

Each cell agent ‘contains’ (or is associated with [4]) one or more network interfaces, going to different neighbouring destinations.$^3$ How we de-mark the boundary between cell and network interface is not a uniquely defined matter, but it is important to the matter of how we restrict the observability of intermediate and uncertain states, in order to bring certainty. We lay out some conventions below.

We shall assume that a network interface promises only packet delivery, not extended message delivery: message delivery is for other agencies with the cells to ensure, building on the promises of reliable atomic packet delivery (in the manner of an OSI layer model).

Network interface agents are the promisers in the mechanics of data transmission and entanglement. Each agent $C_i$ thus has a number of network interfaces $N_j$, which are formally independent of $C_i$. Each network interface agent has registers fulfilling two roles:

3We shall discuss a couple of alternative ways in which the interfaces can keep promises, suitable for deterministic transmission, with more efficient promise keeping at the expense of additional ‘pipeline’ state-memory in the interface agents, to avoid wasting cycles of communication while confirming packets already sent.

3What this containment means promise theoretically remains to be explained. See [4] for a detailed discussion.

for sending and for receiving data intended for its adjacent neighbour counterpart. Network interfaces act as dispatchers, for the serial queue used by each cell for message passing.

The $N_i$ network interfaces act as proxies for the cells $C_i$, making dedicated ‘dumb’ promises, subordinate to the message queue imposed by the cell. The promises between $N_i$ and $C_i$ are thus crucial for building higher levels of entanglement on top of lower layers (figure 5). We introduce two new agents: $Q_L$ and $Q_R$ for the message queues that feed into and out of the link.

C. Network registers

Each network interface possesses effectively two logical ports (i.e. two registers): one for ‘data out’ or sending called $N^{(+)}$, and one for ‘data in’ or receiving called $N^{(-)}$, where $n = 1, 2, 3, \ldots$ labels a particular network interface, attached to any cell node. Network interfaces are formally separate agents from the cells (as required in promise theory, since they maintain independent promises); therefore, we must eventually describe the cooperative promises between the cells and their interfaces too. However, we focus mainly on the network interface agents for now.

Fig. 1: The agent structure of a link, and the direction of data flows (not promises) between them. $C_L$ and $C_R$ may be sender or receiver. Network interface agents for these are denoted $N_L$ and $N_R$, with internal register agents $N_i^{(+)}$ and $N_i^{(-)}$ for sending and receiving respectively. A message sent from the role of sender to receiver is denoted $M$, and the complementary reverse acknowledgment message is denoted $\overline{M}$. Note that, by promise theory principles, we deal with the communication between each pair of agents as a separate set of promises, since the behaviour of each agent is independent.

Let any network interface agent $N_i$, $i = 1, 2, 3, \ldots$ be denoted by a doublet of two registers: $N_i^{(+)}$ for sending, and $N_i^{(-)}$ for receiving:

$$N_i = \begin{pmatrix} N_i^{(+)} \\ N_i^{(-)} \end{pmatrix} = \begin{pmatrix} \text{send register} \\ \text{receive register} \end{pmatrix}$$ (1)

as in figure 1. Figure 2 clarifies the notation or more than two interfaces, distributed across a number of cell agents.

D. Geometry of the configuration (physical symmetry breaking)

The geometry of a link is shown in figure 3, with left and right ends of an axial link. The operation of
reflection may be interpreted digitally as a NOT operation⁴. If the two directions of message travel between left and right pass along separate channels, i.e. full duplex (see figure 3), the orientation of the loop they form also has a topological orientation⁵. As messages pass back and forth they have two eigenmodes: the digital equivalent of standing waves (which we shall use for equilibrium states, and travelling waves, which we shall use to transmit data packets.

### E. Bootstrap of L, R orientations (dynamical symmetry breaking)

Network interfaces, connected for the first time by a network channel, can self-organize to select an arbitrary naming convention or ‘orientation’ for the endpoints. A protocol flips a virtual coin to break the symmetry between left and right, and decide which agent can promise to call itself ‘left’ and which promises to call itself ‘right’. Agents converge on this state of broken symmetry⁶. Thus, they do not need to be assigned endpoint addresses by an exterior authority: geometry alone assigns them designations of ‘self’ and ‘non-self’?; one only needs to distinguish one end from the other in a mutually agreed way. We use the convention L and R for ‘left’ and ‘right’ (non-left or left, as opposed to heads/tails, up/down, black/white etc) for these designations.

By convention, the left agent will send signals TICK and the right agent replies with TOCK, in the language of [15]. We shall also use the terms L-TICK and R-TICK for consistency with the unified narrative about symmetry breaking and orientation of the link.

These designations promising L and R are made by the network interface agents, at the level of packets, and apply only to the link⁸. It is nonetheless necessary to maintain corresponding distinctions for cells via the intended addressee of messages, e.g. to ensure that a message doesn’t accidentally get reflected back to its sender, especially when travelling over long distances. This designation cannot be inherited from the interface card, because a cell has multiple network interfaces. Cells therefore need to refer to one another in the scope of a larger model, which addresses the concerns of messages.

#### F. Intent versus timeless average behaviour

After the initial negotiation of left-right symmetry breaking, to establish the configuration in figure 3, and determine a coordinate basis: L who signals with TICK (or L-TICK) and R who signals TOCK (or R-TICK), etc, two modes of operation can be defined across the link:

1) **Intent free**: an idling or standby phase. This phase may be called ‘timeless’, because no direction for advancement is selected that marks out a unidirectional timelike progression; the system goes as much forwards as it goes backwards, maintaining a steady state equilibrium. Exterior observers see no observable change in the promised state of the link or its endpoints, i.e. no time passes on the link’s exterior clock, and on the interior every forward step is met with a step backwards.

2) **Intentional**: a transitory asymmetric message transmission phase. In this phase, the L – R symmetry is broken, and observers exterior to the link see time advance one tick for each packet sent, for the duration of a message. Any (even) number of non-observable interior exchanges may need to be enacted in order to make this transfer of information happen.

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⁴In the original document, the exchange of vector items was used; such an exchange is a n + 1 dimensional linear representation of a NOT operation in n dimensions.

⁵The direction of the current define something analogous to a magnetic field direction for the loop.

⁶This is like a trivally local ferromagnetic state along each interface-to-interface change, but with no long range correlation between different interface pairs.

⁷This notion of ‘address-less endpoints’ (meaning point to point links in which the addresses are redundant by virtue of geometry) is used in another promise oriented system: unnumbered interfaces in BGP. In a point to point link, the link geometry can prevent misunderstandings about intended source and destination: each endpoint recognizing self and non-self.

⁸Although, for our two agent example, we use the cell designations C_L and C_R, the cells have no natural left or right designation, as they have multiple link dimensions.
Entanglement persists, uninterrupted, through both modes of operation. These two modes are referred to as ENTL and ENTT respectively in the nomenclature of [15]. Throughout both modes, the pendulum nature of exchange continues verifiably, alternately from left to right, and back.

G. Two kinds of symmetry

We refer to two separate symmetries in our description of the link system:

1) Spatial configuration symmetry (layout, characterized by \( L, R \)).
2) Dynamical balance symmetry, relative to (1), characterized by sender/receiver role exchanges \( S, R \) or +, −.

As a purely technical note, the left-right configuration handedness of each link is not significant over long times i.e. over many interactions, when at steady state station-keeping. It is averaged out by dynamical interactions. In this sense, over arbitrary (even) numbers of interactions, the link may be called timeless (like a standing wave), since it is a superposition of two simple Markov processes: it has no interior state that can act as memory, counting like a clock of order greater than one. It is basically a pendulum that cannot be observed microscopically. Its average position is zero, neither left nor right. Individual transmissions, piggy-backed over this pendulum have a handedness (chirality), but even these may average to zero if one disregards their semantic content.

Example 1: A simple analogy would be to think of a grandfather clock. The orientation of the clock does not affect its ability to tell the time: its pendulum does not swing more in one direction than the other, and it doesn’t matter which side we call left or right. Nevertheless, when gears are engaged, the continuous motion drives an asymmetric clockface in a single direction, by breaking the symmetry. The clockface is like a message being transmitted in one direction.

The pendulum (as a Markov process) cannot count or remember any length of time, beyond one tick, but it can drive the transmission of a larger sequence (on the clock face) to keep a time message, modulo the memory size of the clock face. In our example, each network interface is a pendulum, and the clock face is analogous to a cell’s private buffer, for transmitting a message.

- When agents have no intent to direct a message, average equilibrium symmetry presides with exchanges of pendulum packet labelled TICK and TOCK (heartbeats), which can be called timeless.
- When agents intend to propagate a message in a single direction, they use the signals TECK (offer) and TACK (acknowledgment), generating ticks that mark an advancement of time at the end points.

When scaling these methods to aggregate ‘superagents’ (see figure 4), the same two phases are needed at each layer over dependency that combines agent to agent entangled links into higher level abstractions with the same irreducible semantics. Thus we shall refer to these two phases of exchange repeatedly: an equilibrium (steady state) phase, and an intentional disequilibrium (transition) phase⁹.

H. Encapsulation of exterior messages

How we ‘quantize’, or define the atomicity of outcomes, frames the way in which we interpret the units of transfer in message delivery. Entanglement (or irreducibility) of communication allows us to convert non-deterministic asynchronous message channels into effectively deterministic synchronous message channels, by restricting or ‘quantizing’ observability. This is a sleight of hand, based on the voluntary cooperation of the agents involved, but it can be effective.

![Fig. 4: An aggregation of agents working collectively defines an effective entity or ‘superagent’, which acts as one, providing a level of encapsulation. The agent is irreducible, if the agents within are co-dependently bound by interior promises.](image)

The property of entanglement has the consequence that, once a message enters a link, it must either leave it as an indivisible unit, or have no effect whatsoever, and thus each transferrable unit must be wholly containable in the send and receive registers. No observer could see a partial state. Everything entering becomes a state of the collective superagent. In the language of distributed consensus, we can turn these promises into commitments, kept deterministically for single hops, and then build on the increased certainty to work towards larger scale consensus [11], [12], [16], [17].

We packetize messages, as is normal to keep transactions predictable, and thus at least two layers are needed for packetized message delivery model (see figure 5): a network interface and link layer operates on the level of packets, and an ‘intended message’ layer, for aggregating packets into larger messages, operates

⁹This two mode solution has a direct analogue in the solution of any set of constraints, e.g. in the solution of differential equations, with source term. There one has a ‘particular integral’ or transitory response to specific boundary conditions, which dies out away from the source. The ‘complementary solution’ or steady state equilibrium behaviour represents the average behaviour over long times (which is therefore relatively ‘timeless’ compared to the timescale of the transitory changes). In our case, cell agents impose boundary conditions by the ‘intend to send’. When this response has played out, the idling steady state (timeless) behaviour persists.
between the cells. The cells are the intentional agents, originating and consuming messages as part of their larger plan. Network interface agents have intent only by proxy.

Separate entanglements may be established at each level of information promises: it is the entanglement of the network interfaces that allows us to make strong statements about transmission of packet chunks, and the entanglement of the cell queues or application buffers, containing the entire messages, which may synchronize complete ordered messages.

III. MESSAGE STRUCTURE

We divide the discussion into two parts: how data are exchanged across the link, and how messages are packetized and reassembled. Once data have been passed across the link, what the receiver does with the message is none of the link’s business, and thus remains undefined for all scales larger than the region formed by the entangled agents. This reflects the essential autonomy principle of promise theory. Agents, on any scale, can distort or dump data, as enshrined in the law of information integrity (see 7.2.2 of [17]); the purpose of entanglement is to enable the detection of these events.

We shall focus on cells and network interfaces one at a time, from the bottom up, understanding that a close collaboration between the layers is needed for the higher layers to function. For simplicity, we describing the special case of one network interface per cell (a single link). In a 3 dimensional fabric one would expect cells to have four to six neighbours, all with point to point entanglements.

A. Interior message-packet promises (irreducibility)

Data packets transmitted from cell to cell are also formally another kind of agent that make promises about encapsulation of data payload; they are emitted and absorbed by cells that define what we mean by ‘fixed’ locations in a network [4], [18]; the structures promised by messages, a message ID. A message that is considered atomic at the level of cells, may have internal structure at the level of the network interfaces: packets must promise which message they belong to, with the message ID, and also have a message sequence number corresponding to a fragment of the total payload.

A complete message is thus a doublet, i.e. makes two promises:

$$M^{(m)} = (m, D^{(m)})$$, (2)

where $m$ is a unique message identifier, $D_m$ is a data payload, e.g. $m = 1, 2, \ldots$. We do not assume any promises are made about interior structure of the data here.

The packetization implies that messages are super-agents, composed of a sequence of packet agents.
Each packet promises to be a member of the message \( M(m) \), and hence carries both a message identifier and a sequence number for the total ordering of packets within \( M(m) \).

Let a message \( M(m) \), originating at cell agent \( C_i \), be defined as an ordered set of packets \( P \):

\[
M(m) = \left\{ p_1^{(m)}, p_2^{(m)}, \ldots, p_p^{(m)} \right\}
\]

(3)

for some sequence length \( p \). We shall say that a message \( M(m) \) has been transferred from a cell agent \( C_i \) to \( C_j \) when each packet \( p_a^{(m)} \in M(m) \) has been emitted from \( C_i \) and absorbed by \( C_j \), in a congruent order.

Each packet is a tuple consisting of a header vector \( \textbf{H} \), which we shall represent below as a 3-vector (see section D), and a data payload \( D \), which is a scalar, and may be empty (when no message needs to be sent):

\[
p_a^{(m)} = (\textbf{H}_p^{(m)}, D_p^{(m)})
\]

(4)

where \( \textbf{H}_p \) is a header vector, and \( D_p \) is the payload data fragment.

The totally ordered aggregation of all packets belonging to a single message \( D_p^{(m)} \) is thus precisely equal to \( D(p) \), which we might write whimsically (for the association of ideas and mathematical interest only) as a kind of path ordered integral, oriented along the intended narrative of the sequence:

\[
D^{(m)} = P \int p^{(m)}
\]

(5)

If no messages are sent, a link merely tick-tocks along with no average direction. When a cell agent intends a message to be sent to a neighbour, it inserts the message in a packetized form into a serial queue, at one end of the link, which acts as a source. The bidirectional symmetry of the link is now broken by the presence of such a message, on the level of cells. Meanwhile, the link continues in a purely reactive state, transferring single packets from register to register, with no average directional intent. In other words, all directionality arises from the boundary intent promised by cells.

B. Sender and receiver roles, and registers

Packets are transmitted from the sender register of one \( N_i \) to the receiver register of the adjacent network interface \( N_j \):

\[
N_i^{(+)} \xrightarrow{P} N_j^{(-)}
\]

(6)

The paths in figure 1 therefore cross over, or must be interleaved by multiplexing. We do not need to define which method is used here. In both directions there will be transmissions with the role of "intent to send" and "intent to receive". So message headers signal:

\[
\text{header} \rightarrow \text{role} \otimes \text{direction}
\]

The message packet headers thus promise both intent and direction, for the packet layer. A similar header must be promised at all layers that entangle.

Packets (called \text{TECK} \text{L-TICK} or \text{TOCK} \text{R-TICK} ) that represent idling or steady-state exchange, represent an absence of intent (the interface agent signals only that it is alive and treading water). Packets called \text{TECK} and \text{TACK} express asymmetric data transfer (send and receive). We use the symbols from \cite{17} \( \emptyset, +, - \) for these cases:

\[
\emptyset \quad \text{TICK} \quad \text{Idle, pendulum mode}
\]

\[
(+) \quad \text{TECK} \quad \text{Offer / Send (payload)}
\]

\[
(-) \quad \text{TACK} / \text{NACK} \quad \text{Accept / Reject (payload)}
\]
like $S = A_1 \oplus A_2$, makes promises that cannot be attributed to or kept by either of its components $A_1$ or $A_2$ alone, then we say the sub-agents are entangled, and we say that the superagent is irreducible [4]. This happens when promises are mutually conditional.

**Lemma 1 (Entangled with respect to intent I):**

Two agents $C_L$ and $C_R$ are said to be entangled or irreducible if the superagent $C_L \oplus C_R$ enveloping both of them makes a promise that neither of the two agents can make alone. This can only happen if each agent makes promises conditionally on promises made by the other. □

This definition is compatible with the definition of entanglement in information theory [3]. For any promise bodies $I_L$, $I_R$, the necessary and sufficient solution to this condition is given by

\[
\begin{align*}
C_L \xrightarrow{+I_L} C_R \\
C_R \xrightarrow{-I_L} C_L \\
C_R \xrightarrow{+I_R} C_L \\
C_L \xrightarrow{-I_R} C_R.
\end{align*}
\]

The proof is trivial: both sides promise $I_i$ ($i = L, R$) with a dependence on the promise $I_j$ from the other, else they would promise independently which would contradict the definition. If the agents do not promise the explicit dependence on the other in (10) and (12), then (9) and (11) are not complete promises, by the conditional promise law 6.2 of [17], that no dependent promise can be given without accepting the dependent promise of the other, thus $C_L$ must accept $I_R$ and vice versa.

When $I_L$ or $I_R$ changes, these promises may be thought of as cyclically generating an evolving sequence of preconditions, which unfolds as a chain of transaction events, until an equilibrium is possibly reached.

**B. Interior and exterior time and observability**

Entanglement is a co-dependent causal evolution of state; i.e. it works in both directions ‘at the same time’, so we must be careful what we entangle, how ‘the same time’ is defined, and how directionality is arranged. It affects $n$-clusters of agents, where $n > 1$. Promise theoretically, we can observe that there are implicit timescales as a result of irreducible co-dependence being composed from atomic elements:

If we define a timescale by $\Delta t^{(S)}$ at scale $S$, measured according to the clock of an exterior godlike observer (figure 7), with access to all information, then each tick corresponds to a single promise-keeping event. The cells cannot observe these events, which happen in between the ticks of their ‘proper time’ clocks, so we might call this ability to observe the most detailed equilibrating events subtime$^{14}$.

A complete cycle of entangled co-dependent causation leads to a natural coarse-graining of time that corresponds to the aggregation of interspatial events (two agents $L, R$ keeping $+, -$ promises to close the cycle).

\[
\begin{align*}
C_L \xrightarrow{+I_L} C_R \xrightarrow{\Delta t^{(1)}} C_L \\
C_R \xrightarrow{-I_L} C_L \xrightarrow{\Delta t^{(2)}} C_R \\
C_R \xrightarrow{+I_R} C_L \xrightarrow{\Delta t^{(1)}} C_R \\
C_L \xrightarrow{-I_R} C_R \xrightarrow{\Delta t^{(2)}} C_L.
\end{align*}
\]

Entanglement thus implies quantization of both space and time, because nothing independent can happen in an entangled network, but we can only observe entanglement on a coarse-grained timescale$^{15}$. If we refer to $\Delta t^{(4)}$ as exterior time or co-time, and $\Delta t^{(S)}$ for $S < 4$ as interior time, then we can call $\Delta t^{(1)}$ specifically subtime. It is purely local, and not observable by any other agent. The promise of entanglement (codependence) is only observable at a timescale $S \geq 4$. These basic points will inform the discussion of a protocol by which can use entanglement to built a quasi-deterministic communication channel.

The two time rates tick with the passage of the following agents, assuming the sender $S$ is $L$:

| ALIGN ROLE | INTERIOR SYMMETRIC | EXTERIOR ANTI-SYMMETRY |
|------------|--------------------|-------------------------|
| ORIENTATION | CLOCK TICK | CLOCK TICK |
| $L/S \rightarrow R$ | TICK/TECK | $+\Delta P$ |
| $R \rightarrow S/L$ | TOCK/TACK | $-\Delta P$ |

**C. Irreducible superagent picture**

Co-dependent promises, made (and kept) by the endpoints, must be maintained regardless of what other independent promises cells might make to any other agent. This happens when both agents are driven by what happens between them rather than coordinating their independent activities (see figure 6). Our goal in this paper is to explore the use of this property in order to keep strong promises about message delivery. Notice that these co-dependent promises are invariant under $L \leftrightarrow R$, and are thus timeless and without preferred orientation.

The keeping of this entangled state can be implemented in the following signal promises, which may

---

$^{14}$Anyone who has used a version control system understands this as all those moments observers of the document repository cannot see, that lead to what was committed in each observable version.

$^{15}$It does not rule out other forms of quantization at a smaller or larger scale.
Fig. 6: Entanglement results in a new effective picture, with overlapping irreducible superagents. Entanglement (irreducibility) is not a transitive property, as the diagram shows: the overlapping of superagents does not imply a single large superagent keeping the same cooperative promises.

be considered an atomic cycle:

\[
\begin{align*}
N_L & \xrightarrow{+\text{TICK}_t} N_R \\
N_R & \xleftarrow{-\text{TICK}} N_L \\
N_R & \xrightarrow{+\text{TICK}_t} N_L \\
N_L & \xleftarrow{-\text{TOCK}} N_R
\end{align*}
\]  

(14)  
(15)  
(16)  
(17)

Note also that this set is invariant under the symmetry \( L \leftrightarrow R \). All these promises are invariant; they become active and inactive based on the receipt of conditional signals. The repetition of this cycle of promises could be disturbed, in principle, by the sending of a message to propagate data. However, we shall show that the basic entanglement can be maintained even as data are superposed on top of these promises, by defining superposed promises:

\[
\begin{align*}
\text{TECK} &= \text{TICK} + \Delta_+ \\
\text{TACK} &= \text{TICK} + \Delta_-
\end{align*}
\]

(18)  
(19)

(see appendix equations (70)-(75)). To understand how this can help to maintain certainty about the non-local state of the link, we need to explain the non-local relativism of entanglement.

Lemma 2 (Composition of entangled links): The composition of irreducible or entangled links, as in figure 6 cannot itself be irreducible or entangled. □

The proof of this follows from the linear combination omits off-diagonal promises (see 11.1-13.1 in [17]).

D. Single-valued time for paired agents

In the geometry of the link, there are two distinct possibilities for temporal evolution of the irreducible link superagent. We identify these as local and non-local in spacetime. They correspond to how we define the clock by which events move forward on the two ends of the link. When agents are independent, they can each maintain independent state, and hence have independent clocks; but when agents are entangled, or co-dependent, they share all the state that pertains to their co-dependent promises, including a common clock. The two cases are shown in figure 7:

1) Local (weak entanglement): each agent can change independently and generates its own clock ticks, or its own sense of time. Messages may be passed, influencing changes on either side with weak coupling, so changes and observations can also be interleaved (independently) while waiting for messages to be passed. Partial or weak entanglement implies the existence of an independent internal event clock at each cell: the agent can make and act on promises without dependency on its counterpart, except when it comes to sending \text{TICK} - \text{TOCK} packets.

\[
\begin{align*}
C_L & \xrightarrow{N_L} C_R \\
C_R & \xleftarrow{N_R} C_L \\
N_L & \xrightarrow{L\text{-TICK} | R\text{-TICK}} N_R \\
N_R & \xrightarrow{R\text{-TICK} | L\text{-TICK}} N_L
\end{align*}
\]

(20)  
(21)  
(22)  
(23)

The link (as an independent sub-entity of the pair of cells) is constrained to act as a single unit, but other aspects of the agents can make unrelated promises without depending on the other agent, e.g. observe the link and perform other functions at any time, according to the ticks of their independent clocks. For example, they could observe the link and detect if it had stalled. This weak coupling is essential for scaling beyond more than one interface per cell.

2) Non-local (strong entanglement): both agents are dependent on the ticks from their mutual interaction, and the messages passed between them are the only clock they know. All other changes on either side are strongly dependent on the message passing. Complete entanglement implies a shared event clock for the whole cell: the entire cell cannot act or promise anything without being in possession of the \text{TICK} - \text{TOCK} packets.
Cor be driven by the link.

If the link drives all aspects of the agents, they become too fragile, leading to possible failures of the link. This can be imagined as wheels joined rigidly by a crank (in the entangled region), and decouplable gears that can be introduced to drive or be driven by the link.

**Agents need to maintain a locally split brain model**

If cells are completely bound by a strong entanglement constraint, they are entirely hostage to the successful keeping of tick-tick promises, and cannot observe promise state independently in order to detect the stalling of the basic tick-tock promises. If part of a cell is only weakly entangled, it can observe and assess broken promises independently. This suggests an internally split brain approach in which network interfaces (see figure 8) are strongly entangled but other parts of a cell are only weakly entangled.

In effect, an entangled link moderates the flow of information on both sides by (b)locking observability of state. The challenge in using this as a technology is to encapsulate the promise to transfer data such that each packet can only be observed on one side or the other.

The conundrum with this arrangement (see figure 8) is that the passage of time will never be single-valued throughout an application unless we give up locality. Agents need to have a split brain approach to time in order to i) be able to maintain strong entanglement promises, and ii) to be able to observe when all activity has ceased on a link, in order to restart it.

**E. Knowledge propagation (certainty)**

To understand packet delivery with ‘knowledge’ guarantees, implementation is based on irreducibility of ticks measured by a shared clock. The reliable transmission of information, promised by entangled agents, may be used to promise a shared state machine, inferring each others’ state transitions based on messages passed, and thus to effectively ‘know’ certain things about the state of the co-dependent agents. This non-local determinism forms the basis of a throttle on data observability.

Promise theory indicates that certainty is built on the trusted cooperation of individual agents. Entanglement at the level of intentional agents is fragile to the misbehaviour of agents. When signals are sent, each side expects them to be accepted, and acted on in an agreed manner. If agents lie to one another, all bets are off. The basis assumptions are:

**Assumption 1 (Synchronous determinism):** In an entangled link, short control messages (headers) will always be accepted into a dedicated register, if received by an agent at the end of the link. Longer payloads, destined for the applications beyond the link, may not be accepted into a buffer.

This implies that the basis message passing control channel of the link cannot be halted, barring some intermediate catastrophe.

Once primed, the entanglement of end points can form the basis of a simple pendulum/pump/motor, which in turn acts as a clock or generator for transfers. Once the LR symmetry has been broken by insertion of a message (see 7.4.1 in [17]), it will be superposed onto the control channel and passed from one side to the other, if and only if the payload can be accepted by the other side. This assumes that:

**Assumption 2 (Agents are reliable and trustworthy):** All promises are mutually kept and agents are trustworthy during all spacetime events, such as message arrival and transmission.

It is possible for entanglement to be broken, and each of the cell endpoints would be aware of there being a broken promise if and only if the cells were weakly entangled (in a locally split brain picture).

In promise theory, knowledge is defined by statistical assessment of the keeping of promises, so this is not knowledge as defined in [17]. The need for repetitive confirmation may be relaxed in the case of highly constrained contexts, such as primitive machinery of the kind we expect in network interfaces, so we use the term knowledge loosely to really mean information.
F. Homogeneity of agents (spacetime)

The ability to trust agents effectively assumes a standard calibration of both ends of a link against an impartial third party (see figure 9). This trusted party might be common software, or a third party service, but it must exist, else no agent can be sure of what its neighbour will do with data it attempts to send (it is analogous to having the same laws of physics at both ends of the link) [4], [18].

Assumption 3 (Spacetime homogeneity): All agents keep the same homogeneous basic set of promises, according to their agreed left/right roles, because the effectiveness of entanglement promises depends entirely on a uniform conditional basis. □

This is essentially an assumption of non-local trust in the basic behaviours of cells.

Fig. 9: Collaboration requires a trusted calibration. The calibrator could be any implicit ‘godlike’ observer, or permanent non-local synchronization, e.g. use of common software. This is analogous to having the laws of physics the same on both sides of the link.

G. Message semantics

The exterior promises made by messages are:

- All or nothing outcome of data transmission (from \(Q_S\) to \(Q_R\))
- If we consider the sending of a packet from the first imposition in (47) as an operator \(\hat{P}\), acting on a data state \(|S\rangle\), then the operator has semantics:

\[
\hat{P}M = |M + P\rangle
\]

(28)

but the interior time it takes is undefined (four or more entangled ticks). The exterior time is one exterior-tick.

H. Transactional semantics, signal heuristics

A trusted shared-state is maintained by copying local state, from each side, in a continuous chain, and make second order inferences, which build on the trust in the behaviour of the endpoints.

Unlike more usual consensus systems, we are building consensus not about state but about local conservation of data. Data are distinguishable and countable, and there should be neither loss nor duplication of data agents.

Given a declaration of primitive state, an agent can claim instantaneous knowledge about single primitive facts. This is not ‘knowledge’ in the full promise theory sense of accumulated certainty, but more like mutual information.

The promises are encoded as bits in the headers of packets, for packet level transfer, and in the message bodies at the message layer\(^{17}\). The ability to depend on the entanglement needs a second order confirmation of receipt:

We provide three equivalent descriptions of the four stages with different perspectives. The first heuristic schematic involves four promise steps:

\[
S \xrightarrow{\text{TICK}} \text{Here’s what I know} \quad R
\]

\[
S \xleftarrow{\text{TACK}} \text{I now know what you know} \quad R
\]

\[
S \xrightarrow{\text{TICK}} \text{I can depend that you know what I sent} \quad R
\]

\[
S \xleftarrow{\text{TICK}} \text{I can depend that you depend on me} \quad R
\]

(29)

In the second, we may interpret them as follows:

0) Recipient: I know nothing, Mr Fawlty.
1) Sender: (TECK) Here is what I know
2) Recipient:
   - (TACK) I now know what you know
   - (NACK) Que? (return to 0)
3) Sender: (TICK) You received my last message, so I know that you know what I know, provided you haven’t forgotten it.
4) Recipient: (TOCK) You can depend on me knowing that last thing you said, assuming that I haven’t forgotten it.

The second promise is no guarantee that the agent will use data it was sent. To make this binding, in a verifiable sense, is impossible within the scope of the link, except perhaps by analysis of long term repeated misbehaviour at the cell level. \(S\) and \(R\) agents can only ‘take or leave’ what the other offers. The hope is that this stabilizes into an entanglement on which all other certainties can be built.

Consider the promises needed to transmit a single packet reliably from \(N_S\) to \(N_R\), in such a way that \(N_S\) and \(N_R\) promise the location of the packet. We assume that the buffer queues for the messages are ‘externally observable state’, while promises made by \(N_i\) are not externally observable; they are only on the interior of the link.

Readers may wonder if the keeping of a data promise may ultimately be satisfied by sending several packets, when a recipient fails to receive a transmission on first try. In other words, is there ‘retry’? No promise need be one-to-one correspondence with a packet attempt. Several packets may be sent to keep a promise, on

\(^{17}\)A confirmation of the specific message integrity, by return of a delivery hash may be embedded in a header as an implementation detail.
the interior of the link, without breaking protocol, and these retries would not be observable to the cell\textsuperscript{18}.

The third form of the promises in (29), may now be spelled out at a more technical level. We refer readers to appendix B for these details.

I. Assessment for packets

Have we succeeded in maintaining the integrity of a single packet state? How many copies of $P$ were observable in the network? The latter is a slightly tricky question in a distributed system, because of the subjective experiences of observers, i.e. special relativity.

Figure 9 shows the structure of an observation of the two ends of a link. A godlike observer with infinite powers of access might observe zero, one or two copies of a packet, depending on when measurements are taken, on its clock. However, no real agent has such access; each must observe changes available to it, by its own clock. Within an irreducible superagent, only a single copy of a queued message $Q(P)$ exists at the buffer queue $Q_R$\textsuperscript{19}. Other copies of the same information, beyond the link, are naturally outside the scope of discussion.

The interior signalling, within the entangled link, promises exterior certainty about which side LR/SR of the link a packet can be observed reliably, just as long as each side keeps its promises deterministically. One cannot discount the possibility that promises might fail to be kept for unknown reasons, no matter how isolated and apparently deterministic the network agents might appear to be.

Whether $S$ can safely delete its copy in steps 2, 3, or 4 is debatable. The earliest moment at which it could assume that the message is passed is on receiving an acknowledgment. There is no compelling reason to wait for confirmation, except that $R$ wants to know that $S$ intends to delete its copy, which it would not do if it did not receive the acknowledgment or if it died in the meanwhile. There is thus an additional level of certainty in making one more cycle to add the confirmation, which we shall assume henceforth.

A unique semantic label (like a hash), as part of TACK($P$), would make confirmation more precise. However, trusting the behaviours is necessary anyway, so it might be considered redundant in that respect, if one believes the indeterminism of the link has been effectively expunged. A cheaper alternative might be sufficient—after all, we have assumed (assumption 1) that headers must always be received and accepted by the network agents.

Since these interactions are expected (unlike the initial imposition of a packet, we can probably assume that there are no reasonable impediments to receipt of a TACK($P$), and thus being alive is sufficient cause to infer that the message was received, and that agents don’t forget what just happened to them. In this approach, agents promise to give up their autonomy and become entangled intentionally, and the entanglement is what reminds them of this.

The final stage is still ambiguous if the alive message does not come back. Then the link stops altogether, and neither side notices since their time is driven by the exchanges. This last matter is essentially the analogue of the FLP proof that distributed consensus is impossible in finite time. The workaround here involves stopping time itself while the job is done, relative to other parts of a wider network. The cost of certainty is temporary paralysis.

J. Assessment for messages

The promise of once-only delivery cannot be trivially extended to multi-part multi-hop messages, in more complicated topologies, without some work. We must defer the full discussion for a sequel, and make only a few remarks here. It is possible for multiple copies of a packet to be observed, duplicated, and transmitted around a network, if agents fail to keep the necessary promises, no matter whether out of ignorance or malice. This is not specifically a weakness of our scheme: it is not easy to promise a negative result.

Nor is it possible to prevent unexpected behaviours: since no agent can make a promise on behalf of another. There are two pragmatic ways to localize the responsibility for intended outcomes to the end points, away from intermediate interference:

- One is to used shared secrets or encrypted messaging to make corruption by ‘man in the middle’ interference detectable. This need not be promised at all layers in a communication stack: high level encryption would suffice for detection by the intentional agents. See the notes in section IV-K.

- Another way is for each packet to make a separate and uniquely labelled promise (see section 3.12 in [17]) by promising a unique desired state. If each unique and intentionally different promise has its own label, and then duplication may be detected, assumed redundant, and ignored idempotently.

Idempotence of promises means that a promise repeated $n$ times is the same as the promise given once\textsuperscript{20}:

$$S \xrightarrow{+M} R)^n = S \xrightarrow{+M} R.$$ \hspace{1cm} (30)

Idempotence must place a role in promising uniqueness, where we don’t have complete control over causation. Just as endless TICK and TOCK cycles promise

\textsuperscript{18}Once we enter the realm of multipath, multihop networking, at the cellular level, a more complicated story is needed concerning the idempotence of signals (see section IV-J), because assurances about the link cannot replace assurances about what is kept in intermediate buffer memory, which becomes part of the effective linkage, at the scale of a message. This topic is deferred to a sequel.

\textsuperscript{19}This requires some justification, however, since the link alone cannot make this promise; idempotence of $P$ must also play a role (see section IV-J).

\textsuperscript{20}Telling you twice that we owe you 100 dollars doesn’t mean that we owe you 200 dollars.
nothing new (except freshness), so repeated intentional messages signal nothing new, and no advancement of state. Efficiency can, of course, be compromised by excess copies (the cost of repetition), but no confusion or duplication of intent would be signalled, provided distinguishability were managed properly, by idempotence of promises. The bottom-up design of the entanglement networks seeks to minimize this possibility of duplication, but we have to defer that discussion to the sequel.

K. Man in the middle: interference and intentional forwarding

What if an agent could insert itself into the middle of a link and imitate the end points \( C_L \) and \( C_R \)? Would this invalidate the promises of entanglement, as in the quantum mechanical case? This is quite easy to do, in principle, because no secret knowledge is required to run the protocol. Such an insertion of an intermediary could be used as a feature or as a bug (an attack). The insertion of a switch or router for multi-hop forwarding uses precisely this approach to deliver packets by chains of voluntary cooperation (see chapter 11 of [17]). Alternatively, a wiretap insertion for breaking security promises would be considered an intrusion.

From promise theory we know that the insertion of intermediate agents renders unconditional promises impossible, because of the basic locality of promises—that no agent can make promises on behalf of any agent other. To establish a similar level of assurance to keep promises through third parties, one acquires the burden of a web of conditional assurances, which grows like the square of the number of intermediaries, unless complete trust in intermediate agents can be assumed. This is similar to the design and cost of building blockchains (the principle is the same). This is a complicated topic, so we shall only make some simple points here, and defer a proper discussion for a sequel.

Between a sender \( S \) and receiver \( R \), an intermediate agent \( I \) could receive packets and pass them on without alteration, invisibly tapping the channel. Or it could become a new endpoint, blocking transmission in one direction and masquerading as the blocked agent. In either case the point to point protocol cannot protect against such an abuse of intent, so long as there is no authentication of the agents.

![Fig. 10: What if an agent could insert itself into the middle of a link and imitate the end points. This is quite easy to do, if no secret knowledge is required to play the protocol game.](image)

Could the end points detect tampering without extra bits? At the physical level, this is doubtful. In the current implementation, any agent can act as an endpoint, and there is nothing to distinguish any agent from the next. What we understand, implicitly from blockchain [13], [20], [21], is that detection of tampering requires something like the longitudinal entanglement of all agents in a chain, or a binding to a trusted third party. The problem for a network protocol is that explicit trust is broken by every inserted host in a chain. Network agents cannot forward data without going through an external host node, so to extend the current approach to multi-hop architectures requires full trust in the entire infrastructure, as well as additional reasoning.

Ignoring the multihop issue for a moment, a single wiretap would be enough to lead to spoofing. An intermediate agent would be able to fool sender or receiver into believing in is a consensus when there were, in fact, none. These concerns can be addressed in various ways, from physical isolation to encoding measures. At the packet level, one can only promise to know that the last tick or message was received, not whether a subsequent acknowledgment was sent, but not received. Links can therefore be stalled and spoofed here too. A responsibility for the integrity of knowledge, like other properties, is pushed to the ends of the link. One way to build in tamper-proofing would to entangle sequential message packets by a simple encryption of the packets, essentially by cipher blockchaining.

The lowest level physical links are those most vulnerable to the physical security of their wires and channels. Higher level derivative entanglement could more easily embed privacy through encryption, making detection of tampering straightforward. These matters are subtle and we shall not discuss them further here.

V. ENTANGLED LINK FUNCTIONALITY

The purpose of an entangled link is to encapsulate deterministic transmission of data, transparently, packet by packet. By equilibrating a message \( M_S \) to an identical image \( M_R \) at another location, before revealing it to the recipient, we can increase the knowledge about consistency of state for mission critical applications. This method is not a panacea, and must work in a suitably curated context, but we contend that it offers a foundation for reliability.

Philosophically, the idea of entanglement opens for a discussion of many deep ideas about relativity and mutual knowledge, and how the concept of ‘consensus’ can even make sense across a spatial region, limited by the propagation of packets. These questions are familiar from modern physics, but their information theoretical counterparts are only just being appreciated. It is not the place for that discussion here, but informed readers may recognize the issues that connect space-time and scale to the propagation of information.

Our motivation is that we might use this bottom-up approach to build distributed applications, in which key data are in a synchronized state at all times. This seems plausible, either within a datacentre, or even across the
planet, with certain provisos. The essence of a solution is how to stop the clocks for certain observers, over a bounded spacetime region, while hidden processes continue to work unnoticed within. It is a quantization of observability over a spacetime interval.

This is not a new idea: current approaches to consistency using locking [22], master-slave systems [11], [12], or blockchain [13], [20], [21], to similar effect, operating across TCP/IP. All scale with significant costs. In our approach, we use several signals back and forth between each node for every packet. What we win from this is synchronized data at every observable step. One has to be cautious about the scaling of promises claimed, as entanglement and consensus may be no less expensive to maintain, but the reorganization inspired by information theoretical entanglement could help to optimize the problem. Centralized coordination, either by locking, queueing, or calibration services, atop TCP/IP, works well enough for many cases where one can solve consistency by brute force. Our approach lends itself to a different kind of lightweight transactional network architecture, designed for determinism in each step. The virtues of our approach remains to be discussed in detail.

In the remainder of this section, we review the core concepts, which perhaps become buried in the technicalities, with a more pedagogical eye.

A. Agreement

Consensus (multiparty agreement) arises between two agents when they agree (see section 8.4 in [17]). The steps for promise theoretic agreement are:

1) (+) Share an invariant promise proposal.
2) (−) Agent 1 observes/accepts proposal.
3) (−) Agent 2 observes/accepts proposal.
4) (+|−) Agent 1 signs proposal if accepted.
5) (−|−) Agent 2 signs proposal if accepted.
6) (−) Agent 1 observes signature.
7) (−) Agent 2 observes signature.

There is an implicit partial ordering in these steps, encoded via conditional promises, and their implicit order. After all promises have been kept, both agents can be said to have agreed or reached a consensus, and a state of common knowledge.

The steps can be simplified, when the proposal comes from one of two agents:

| AGENT | PROMISE/INTENT |
|-------|----------------|
| 1     | S Share presigned proposal |
| 2     | R Accept proposal and signature and ack. by signing proposal |
| 3     | S Accept R’s signature (S and R now agree and know it) |
| 4     | R Receive accepted signature from S (everyone finished) |

This is the version we use for running a transaction protocol. The steps are encoded into the protocol for entanglement as follows:

| AGENT | SIGNAL | PROMISE/INTENT |
|-------|--------|----------------|
| 1     | S      | TECK Share P into N_S |
| 2     | R      | TACK Copy P into N_R send acceptance |
| 3     | S      | TICK Delete P from N_S and (set P in Q_S not observable) |
| 4     | R      | TOCK Move P from N_R to Q_R (make P in Q_R observable) |

B. Timescales

There are hidden assumptions behind promises of consistency. The first crucial assumption is that the proposal or desired outcome is invariant over the lifetime of the consensus process, else one could not stabilize a transmission in a particular direction. The proposal exposed in the first step of the agreement process, described in the previous section, may not change as the agents go about their interior promises to observe, copy, and agree to it. In the language of clocks, the object of agreement, in any common knowledge problem, needs to be persistent on a timescale longer than the promises to abide by the intermediary steps. So, whereas one typically talks about ‘correctness’ in computer science (a semantic assessment), it is more a question of stability (a dynamical assessment), or invariance of assumed targets, during the key change processes [17], [23].

So, to converge on a stable target, it is assumed that the timescales (as measured on the clock of some god-like observer) for the lifetime of the exterior promises to transmit with integrity, must be significantly longer than the timescale over which the interior promises are defined and kept, by a good margin, else one is racing against a moving target:

$$\Delta t_{exterior} \gg \Delta t_{interior}.$$ (31)

It is not coincidence that this is also the condition of equilibrium, with equilibration or ‘relaxation’ time $t_{relax}$ for transactions:

$$\Delta t_{exterior} \gg \Delta t_{relax} \gg \Delta t_{interior},$$ (32)

or equivalently:

$$\Delta t_{common \ knowledge} \gg \Delta t_{transaction} \gg \Delta t_{TICK},$$ (33)

In our technical implementation, this translates into the rates of interior TICK /TOCK processes relative to the rate of new messages $M$.

$$\Delta t_M \gg \Delta t_P \gg \Delta t_{TICK},$$ (34)

We expect to be able to achieve consensus about $M$ is there are many more TICK events than there are new messages. This (hopefully) seems like an obvious point, but most consensus discussions brush
over such limitations. The upshot is that an ideal technology should seek to maximize the rate of interior equilibration. Faster is always better.

The core assumption (often unstated) is, therefore, that consensus equilibrium systems is that the data cannot be allowed to change faster than the superagent can reach equilibrium or consensus. Moreover, things that depend on the value need to be frozen for the duration of the message transfer, so \( M \) is a slowly varying quantity.

C. Playing with time in a split brain world

The split brain model, within a cell, allows a cell to detect when a link has stalled. To accomplish this, each cell maintains effectively two kinds of clocks: one engaged in link activity, and one sampling the other for stalled state. The clock that drives each link, shared by the endpoints of a link, is thus watched over (on each side) over by processes synchronized by the cells’ clocks, which can observe all the network interfaces they are connected to. If message exchanges time out, according to the observer clock, some recovery is in order. Recovery actions depend on the larger topology, so we shall not comment on details here. Alternatively, the link simply dies, and time effectively stops for the entangled parties. No data are sent or received. It may be possible to restart the stalled link in some cases (by repairing a broken wire, for example).

D. Scaling consistency

A collection of consistent transactions must lead to a consistent collection, regardless of how we packetize messages. However, it is not obvious that other forms of composition, such as end-to-end serial compositions of links, can automatically assume the same promise of consistency (see chapter 11 in [17]). Promises are not transitive properties, and do not therefore extend across intermediate agents, without more effort. This means we can’t automatically assume entanglement properties of a journey composed to several legs.

Because of the timescale constraints, entanglement works most effectively over ‘small’ amounts of data, and small regions of spacetime, but becomes untenable as we try to include more information, because the ratio of interior to exterior promises grows, creating long relaxation times. This is the same as for classical consensus protocols, but the difference lies in the fine-grained observability of the process, which opens for new routes to certainty and recovery in case of trouble.

Network links only have meaning in the context of a larger process, some of which extends beyond the region of entanglement. If an entire cell crashes on one end of a link, and loses a large part of its partially sent or received message queue, we cannot say anything about recoverability of the state of the cell in the future, or what the link’s recovery might do to it. A consequence of entangling the link is that there is an implicit coordination of the connected cells too. In order to recover one cell’s state, neighbouring cells’ states may play a part in the recovery. Catastrophes at a scale of cells provide no automatic context for an automated recovery. Application recovery is therefore a separate issue. This is a normal scenario, in any technology, and it means that entanglement and recovery can only work within reasonable bounds.

Once a data packet passes outside a region of entanglement (the interior of a link), its value can drift away from that on the other side of the link, independent and unconstrained. Because equilibrium takes (interior) time to establish, a unified exterior state can be promised only after these interior promises have been kept. The key to quickly promising consensus lies in managing the scope (or spacetime region) over which data are equilibrated.

Within the bounds of an entangled link, this is handled by quantizing ‘events’ in such a way that intermediate states are not observable. One can try to scale this approach, for higher level communications too, by defining a new meta-process on top of the lower level processes, that spans multiple entangled links, and passes a new level of TICK /TOCK messages end to end. The whole story may thus be repeated, at a slower rate and on a wider range, forming a reliable tunnel, analogous to figure 8:

- Forming a split brain within the application, and equilibrating the state of application endpoints \( A_S \) and \( A_R \), application packet by application packet, over a distributed tunnel.
- Using destructive observation to teleport packets from application \( Q_S \) to application \( Q_R \).

Entanglement turns a passive equilibrium into an active co-determined one. A change of state on either side propagates instantaneously and deterministically in exterior time to the other end of the link, just as in other distributed consensus databases.

E. Impossibility theorems

The well known FLP proof and the ‘General’s Problem’ about consistency and asynchronous uncertainty challenge the designs for approximating consensus in contemporary technologies. Solutions building on TCP/IP networks tend to focus on the state of data,
rather than on the timescales over which the states can be promised, since delivery times are not easily quantifiable in TCP/IP networks. Our observation here is that time plays a crucial role in the meaning of determinism, and that one can use this to greater advantage in a reprioritized implementation.

The FLP result says that consensus is impossible, in an asynchronous system, where agents only might be unreliable. The simplest improvement might therefore be to avoid the indeterminism of asynchrony, to the extent that this is possible. The strategy in an entangled link is to engineer synchronicity back into the communications by adding a management layer ‘underneath’ conventional communications (or in promise language, on the interior of the network agents). Asynchronous behaviours get coarse-grained away by restricted observability, leading to an exterior promise of quasi-synchronous transmission. This is a workaround of the FLP result.

F. Failure modes

If a message does not arrive, for some reason (there are not many plausible reasons for failure at the level of entanglement), then the link itself may simply stop transmitting. With a split brain cell agent, this is detectable, even as the link dynamics are given the primacy to drive progress. Comparing to a TCP/IP delivery:

| Condition | TCP/IP          | Entangled |
|-----------|----------------|-----------|
| Send      | Impose / Collide | Scheduled slot |
| Not ready | Drop packet, recover | Try again. |
| Queue full| Drop packet, recover | N/A       |

The additional certainty of message delivery means that the need for an infinite number of messages (the Generals’ Problem) is formally rescinded. With fully independent clocks, endpoints might assess a failure in the imposition of an asynchronous message, an inconvenient moment. In an entangled link, messages are promised according to an agreed schedule, and this schedule literally stops time for both parties until recovery is possible.

This implicit notion of time is fundamental to the process of acknowledgement. Normally one does not take into account the relativity of the agents; in our case, relativity is built into the design.

VI. BUILDING RECURSIVE ENTANGLEMENT

We are focusing here on the engineering principles involved in keeping single link promises, both theoretical and practical. The key approach is to scale the definitions of agents and packets, such that the indeterminism of the interior agents promises are re-framed as quasi-deterministic exterior promises. The next steps are to build assurances over wider areas, spanning multiple hops. This introduces plenty of new issues to be discussed in a sequel.

The entanglement method is extensible to arbitrary levels of abstraction, in principle. Being able to promise reliable point to point delivery allows one to reason about delivery at any scale, but it does not ensure the inevitable correctness of messages, which are the responsibility of applications. This requires a trusted platform too.

Given the cost of entangling agents, including the energy cost of maintaining a TICK /TOCK, this might not be a method one would suggest lightly for communications in any context; however, in more stringent circumstances, it seems well suited for assuring data replication, e.g. in mission critical scenarios, or disaster recovery of high value data. Further issues have to be discussed before we can build applications on top of it.

This includes the routing of messages through a full network, and also the effects of serial composition of links, each of which independently plays with time. The rapid circulation of tokens could make multi-hop journeys more sensitive to channel differences. We might foresee the possibility of ‘timing storms’, or unstable modes of oscillation, at the interfaces between hops with different relative rates of promise keeping. This could require some damping mechanisms to be incorporated, over wider areas, especially on inhomogeneous networks with uneven latencies.

In short, to scale the entanglement, we may not automatically assume that a serial composition of links will keep the same promises as a single link. However, we can reimplement they protocol recursively on top of the links. Schematically, the approach will be the same at all scales; one sends a promise proposal:

\[ M = \begin{pmatrix} \text{Intent} \\ \text{Ack of Intent} \end{pmatrix} \]  

at some scale, expecting a complementary form in return:

\[ M' = \begin{pmatrix} \text{Intent to ack} \\ \text{Ack of Ack} \end{pmatrix} \]

If one can avoid multiple (redundant) causal pathways, this interaction remains ‘simple’, else it might lead to new forms of interference. One way to avoid it is to employ a spanning tree approach to wide area coverage [24].

Each higher level of data payload, in a message \( M \) relies on the promises below it for its atomicity and integrity (as represented by figure 5). By reprioritizing network functionalities, redesigning the layers starting from the bottom, it should not be necessary to build many layers. The assumption of lower level reliability at every scale, which may be assured in turn by the application of such ‘turtles’ all the way down.

VII. SUMMARY

We have outlined the description and scaling of reliable point-to-point communications links, based on
promise entanglement. We showed that a system using such links behaves as a quasi-deterministic system (i.e. one in which cause and effect appear synchronous according to a shared clock). The entanglement property may be effective provided all network agents maintain the same uniform set of promises, and the amount of transmitted information per packet is small. This allows fast equilibration of state, and straightforward reasoning about data delivery, including data consistency.

Once data emerge from the entangled link region, no further promises about data can be made; e.g. if an entire cell or application crashed, and lost its runtime state, say, half a transmitted message, we might not be able to say anything about the relative states of sender and receiver when it came back. So an entangled link cannot be expected to recover a session whose larger context has been lost. This is as expected, and the connected parties would still have to detect the collapse, and determine their own response to the failure at their own level. Such events are likely rare, however, compared to smaller contentions over network delivery, especially in highly utilized environments like cloud computing infrastructure; so, it seems likely that there is a beneficial use case for such an approach.

In the sequel, we shall address the routing of messages between higher level applications, through multiple ground level cells, in order to promise average deterministic outcomes from non-deterministic multi-path networks.

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APPENDIX

This appendix describes implementation details of promises and agents involved in the chain of custody in an entangled link. There might be several equivalent representations of these promises, so we seek a necessary and sufficient fundamental representation.

A. Buffer queues and observability

For completeness, and precision, we declare the semantics of queues. Referring to the figure 5, in which cell $C_S$ has the sender role $S$, with an interior message process $M_S$, and $C_R$ is the receiver cell with role $R$, and message recipient $M_R$.

- Data in a packet $P$ begin in the messaging process $M_S$, contained by $C_S$, and are pushed into a buffer to send to another agent $C_R$, which promises to accept without impediment:

$$M_S \xrightarrow{P} Q_S \quad (37)$$

$$Q_S \xrightarrow{P} M_S \quad (38)$$

The information in $P$ does not disappear from $M_S$, but (to account for its transmission) we enter it into a queue (Last In First Out) structure. The contents of this queue $Q_S$ are observable to the message originator $M_S$, including its network interface transmission register $N^{(+)}_S$ on a packet by packet basis:

$$Q_S \xrightarrow{+Q_S(P)} M_S \quad (39)$$

$$Q_S \xrightarrow{+Q_R(P)} N^{(+)}_S \quad (40)$$

The $Q(P)$ notation is shorthand [17] for the queue’s representation of the packet, dependent
on its value \( P \). This is conditional on receiving \( P \), i.e.:

\[
Q_S \xrightarrow{Q_S(P)} N_S^{(+)} = \begin{cases} 
Q_S \xrightarrow{(P \in Q_S) \cap P} N_S^{(+)} \\
N_S^{(+)} \xrightarrow{-P} Q_S
\end{cases}
\] (41)

We write the normal shorthand \( Q_S(P) \) for \( Q_S \)'s interior representation of \( P \), and \( Q_R(P) \) as \( Q_R \)'s representation of \( P \), and so forth, where it is understood that \( Q(P) \) has the value \( P \).

- When ready to send, the network interface pulls promised packets from the send queue, and promises its own representation \( Q(P) = P \), based on \( Q_S(P) = P \):

\[
\begin{align*}
N_S^{(+)} & \xrightarrow{-Q_S(P)} Q_S, \quad (42) \\
N_S^{(+)} & \xrightarrow{+Q_S(P)|Q_S(P)} N_R^{(-)}, \quad (43)
\end{align*}
\]

This is the prerequisite that initiates transmission in (50). Note that the link representation \( Q(P) \equiv \text{TECK}(P) \) in our protocol notation.

- We define \( P \) to be ‘observable at \( X \)’ when

\[
Q_X \xrightarrow{+Q_X(P)} M_X, \quad (44)
\]

in other words the message can be received when this promise is made, and the message is received when

\[
M_X \xrightarrow{-Q_X(P)} Q_X, \quad (45)
\]

has been kept.

- Observability may be rescinded if the promise is deleted:

\[
Q_S \xrightarrow{-Q_S(P)|\text{cycle complete}} M_S, \quad (46)
\]

in other words, the queue ceases to promise the packet \( P \) in its buffer. When the four phase cycle is complete, the packet \( P \) becomes observable at \( Q_R \) and non-observable at \( Q_S \).

The causal determinism rests on making these transitions conditional on the appropriate set of prerequisite conditions.

B. Interior packet promises, signal details

The four stages of an interaction may be described as follows (see figure 5). Readers are reminded that every symbol representing a promise agent implies independent behaviour, and that information is only observable by those to whom it is promised. The message queues of the sender and receiver play an important role, in these steps, as the intermediary that decides where packets are allowed to be seen. The queue (see appendix A) is the interface between the split brain entanglement zones of the cells.

1) The sender \( S \) pushes data \( P \) into its send queue \( Q_S \) (see figure 5), which accepts and promises that the value is ‘observable’ at the sender queue location:

\[
S \xrightarrow{+P} Q_S \quad (47) \\
Q_S \xrightarrow{-P} S \quad (48) \\
Q_S \xrightarrow{+Q(P)|P} S, N_S^{(+)} \quad (49)
\]

So \( P \) is now observable at \( S \) by whatever exterior parties might try to look (and are promised access). When \( N_S^{(+)} \) accepts it from the queue for transmission, it promises to share it with \( N_R^{(-)} \), conditionally:

\[
\begin{align*}
N_S^{(+)} & \xrightarrow{-Q(P)} Q_S, \quad (50) \\
N_S^{(+)} & \xrightarrow{+\text{TECK}(P)|Q_S(P)} N_R^{(-)} \quad (51)
\end{align*}
\]

The registers \( N_S \) and \( N_R \) are not publicly observable by \( C_S \) or \( C_R \), so no observer can see intermediate states of transmission, until \( N_S \) and \( N_R \) promise explicitly to update the observability status of data in the respective queues \( Q_S \) and \( Q_R \).

The queue buffer is quite important in bounding the scope and limits of entanglement, i.e. simultaneous co-determination of state, and according to whose clock. If the entangled state extended beyond, the cost of entanglement might not be achievable relative to the rate of independent changes at either end.

2) The recipient \( R \) promises to always accept the TECK packet, but may promise to accept the TECK packet payload, or not:

- **Accept:** If \( N_R \) accepts the payload \( P \),

\[
N_R^{(-)} \xrightarrow{-\text{TECK}(P)} N_S^{(+)} \quad (52)
\]

then it can promise that it shares the state of the sender, and it pushes this shared state to the queue \( Q_R \):

\[
N_R^{(-)} \xrightarrow{+Q_R(P)|\text{TECK}(P)} Q_R \quad (53)
\]

\( N_R \) replies with a TACK to acknowledge receipt (or possibly a NACK to reject it):

\[
N_R^{(+)} \xrightarrow{+\text{TACK}(P)|\text{TECK}(P)} N_S^{(-)} \quad (54)
\]

Now both queues can promise co-determined \( P \), but only one side promises to expose it to the wider cell \( C_R \). This restriction of observability prevents the application clock from advancing for the world beyond the interface. The data \( Q_S(P) = P \) and \( Q_R(P) = P \) are now duplicates (co-determined by the sub-time exchange), and there is overlapping mutual information \( P \).
• **Reject**: If $N_R$ rejects the packet, it cannot claim to share the same information as the sender, so it does not promise to push anything to $Q_R$, and instead returns a NACK message:\[
N_R^{(+)} \xrightarrow{-\text{NACK}(P) | \text{TECK}(P)} N_S^{(-)} \tag{55}
\]
This new state at $R$ co-determines that $P$ should be removed from $N_S$, and the sequence ends.

3) If a packet was accepted, then the significance of the next exchanges continues to have meaning within the atomic transaction, otherwise the link does not advance.

**Accept**: $N_R$ acknowledged receipt of $P$ with TACK, and $N_S$ promises to accept acknowledgments of receipt,
\[
N_S^{(-)} \xrightarrow{-\text{TACK}(P)} N_R^{(+)} \tag{56}
\]
\[
N_S^{(+)} \xrightarrow{+\text{TICK} | \text{TACK}(P)} N_R^{(-)} . \tag{57}
\]
So $N_S$ infers that its promise to send has been kept, and it can therefore withdraw that promise without impediment:
\[
N_S^{(-)} \xrightarrow{-\text{TICK}} N_R^{(+)} \tag{58}
\]
\[
N_S^{(-)} \xrightarrow{-\text{Q}(P)} Q \tag{59}
\]
\[
Q_S^{(-)} = \text{Q}(P) \xrightarrow{-\text{M}(S)} \text{M} \tag{60}
\]
Now $Q_S$ knows that the receipt is known to the sender, and that it will not try to resend it, so it is safe for the receiver to reveal its catch. $R$ signs off by signalling back TOCK to $S$, indicating that its copy has been revealed:
\[
N_R^{(+)} \xrightarrow{+\text{TICK} | \text{TICK}} N_S^{(-)} \tag{61}
\]
When $S$ accepts the TOCK, it is safe to inform the message $M_S$ application that delivery of $P$ is complete, e.g.
\[
Q_S \xrightarrow{-P} \text{M} . \tag{62}
\]
This completes the detailed autonomous semantics of the signalling of a single packet $P$ between two agents that are entangled. Readers might be surprised at the number of detailed chain of co-dependent promises that are needed when there is no automatic assurance of determinism, but this is just accounting for the signalling of a single packet after a certain number of retries.

C. Packet agent structure

In this section, we deal with the interior structure of messages promised between registers $S$ and $R$ of any network interface $N$, from their perspective. This is complicated by having a nested vector structure, with a hierarchy of interpretations.

Because the reflection semantics at the endpoints acts dumb reflectors on all four components of the $H$, the encoding of intent a message $M$ is sent by one network agent to another. The sender or initiator carries the intent to transmit a message (a + promise) with header $H$, while the recipient is the target of the message. The recipient responds with a complementary message $M$, whose header has the complementary structure (a - acceptance promise) with header $H$.

A message $M = (H, D)$ is a doublet consists of a header $H$ and a payload $D$. A payload may be optionally empty, i.e. $D = \emptyset$.

D. Header structure

Labels $L$ and $R$ stand for ‘left’ and ‘right’, and refer to the distinct ends of a network connection. The assignment of left and right is arbitrary (a result of some dynamical symmetry breaking process), but we assume it remains invariant during the interactions. Left is defined as the agent that sends ‘tick’ (or L-TICK), and right is the agent that replies ‘tock’ (or R-TICK).

\[\text{In earlier documents, it returned TOCK to reject.}\]
Fig. 12: A message must satisfy this complementary property at all times, at all scales involved in message passing. At the link layer, intent is kept deliberately simple: to reach the other end, and acknowledgment is a simple matter of reflection. At the level of a message, intent involves the arrival of a specific string, so acknowledgment is more complicated.

Boldface vectors $H$ denote intent-acknowledgment 3-vector message headers. Message headers promise to signal intent of a transmission in one of three cases $(\emptyset, +, -)$. In addition, they encode the intended recipient of the message (one bit for left or right $(L, R)$), because a message may conceivably be misread or reflected back by the physical environment to the initiator. So the header data need

$$M = \begin{pmatrix} (\text{intrial to ack}) \\ (\text{ack of intent}) \end{pmatrix}$$

These six cases can be represented in three bits, or in the components of a 3-vector:

$$H = \begin{pmatrix} \text{Intent} \\ \text{LR-Ack} \end{pmatrix}$$

$$\text{promise} = \begin{pmatrix} (\emptyset, +, -) \\ (L, R) \end{pmatrix}$$

$$\text{bit rep.} = \begin{pmatrix} 0/1 \\ 0/1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

Note that the encoding of idling could be symmetrical with either 0s or 1s. The final choice takes one of each, as is explained below. A link transmission header, in either left or right direction may take one of the following forms:

$$\begin{align*}
\text{L-TICK} &\leftrightarrow 0 \oplus L2R \leftrightarrow \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \\
\text{R-TICK} &\leftrightarrow 0 \oplus R2L \leftrightarrow \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \\
\text{L-TECK} &\leftrightarrow + \oplus L2R \leftrightarrow \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \\
\text{R-TECK} &\leftrightarrow + \oplus R2L \leftrightarrow \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}
\end{align*}$$
When no messages are being sent, and the boundary conditions on the link from the parent cells are only symmetrical over whole numbers of cycles, but we can’t see this at the link layer, which remains a ticking clock of modulo 2, skipping or treading water. We thus write the components as vectors that encode the orientation of the message relative to the endpoints. Although the promises reach a promise equilibrium, the dynamical realization has a handedness in virtue of the broken symmetry. This originates essentially from the order of preconditions imposed by the cell agents, in the form of boundary constraints on the dynamics of the link.

E. Packet header 3-vectors: (in/out) complement

As data circulate between sender (intender) and receiver (acknowledger) roles, two parts of information remain anti-correlated as complement reflections of one another. The purpose of entanglement is that it pushes intent to the far extrema of the link, i.e. to the edges where boundary conditions are determined, and away from the places where noise can enter en route. This has the effect of making noise less of an issue. As long as we maintain entanglement, at both link and transmission layers, we effectively know the state of the other agent, because the states of the sender and receiver are mirror images within each channel of intent.

In practice, the intention to send (without the payload) is merely a direction vector L2R or R2L indicating who is sender and who is recipient: a simple auto-addressing scheme for a point-to-point link. Thus it always points in the direction of travel, while the acknowledgment component continues to tick-tock. When the tick or tock matches the symmetry breaking TOCK, the promises we intend to keep here:

Let’s define the bar operation to be the simple one’s complement of each component. Then we see that

\[ \text{TICK} = \text{TOCK} \] (76)
\[ \text{TOCK} = \text{TICK} \] (77)
\[ \text{L-TECK} = \text{R-TACK} \] (78)
\[ \text{R-TECK} = \text{L-TACK}. \] (79)

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\[ \text{L-TECK} = \text{R-TACK} \] (78)
\[ \text{R-TECK} = \text{L-TACK}. \] (79)

Note, to fully expose the L,R symmetry, we could further regularize the notation and define:

\[ \text{TICK} = \text{L-TICK} \] (80)
\[ \text{TOCK} = \text{R-TICK} \] (81)
\[ \text{L-TICK} = \text{R-TICK} \] (82)
\[ \text{R-TICK} = \text{L-TICK}, \] (83)

making the idling phase and the transient message phase formally similar. Indeed, with this notation, there is a simple promise correspondence:

\[ \text{TICK} \leftrightarrow \emptyset \] (84)
\[ \text{TECK} \leftrightarrow + \] (85)
\[ \text{TACK} \leftrightarrow - \] (86)

This complementarity property is entangled with the entanglement! In other word, it holds as long as the mutual promises are kept. If it fails to be true for whatever reason, then entanglement has been lost and an error has occurred. The link must then be re-established for continuation of a message. In other words, ‘what I know about me’ (local state) (intent) and ‘what I know about you’ are compared and validated by this header property alone, as long as both agents keep the same calibrated promises.

F. Steady state interaction

The simplest version of the interaction has a single alphabet, and symmetrical idling (figure 14) and asymmetrical message (figures 15 and 17 for left to right, and figure 16 for right to left) modes of transfer.

The promises we intend to keep here:

- To maintain entanglement of the link, ensuring a sense of shared time on the interior of the link. This can be used to enable ordered delivery on a single serial connection (prove this) within the scope of the entanglement.
- To utilize a consistent tick-tock encoding and exchange throughout all message passing (a single ‘carrier wave’, in contrast to the two mode carrier encoding in the ENTT, ENTL version).
- No promises can be made about ordering over parallel channels.
- The promises made by the payload are undefined.

Note that the ability to distinguish left from right depends on the timescale of measurement, i.e. on whether one measures time intervals preferentially in even (the timescale of measurement, i.e. on whether one measures time intervals preferentially in even (2n) or odd (2n+1) numbers of ticks. Since taking a large number of ticks makes this distinction irrelevant, one can say that behaviour that is, on average, the same in both directions is undirected on average. This limit is what is important to the long term behaviours of a link, while the short term fluctuations may be directional. This means we can send short term packets comprising messages, intentionally, in either direction without sacrificing long term coherence.

Note, that the encoding of TICK and TOCK don’t need to satisfy this property, because the natural choice from a purely information perspective might be TOCK = R2L ⊕ I (rather than T), however by assuring the complement explicitly in (71) we can maintain validation of the entanglement explicitly on every reflection.

\[ 21 \]
packet sent from right to left by jumping onto a clear TOCK package. In both cases, the link only needs to
detect whether the registers signal a directionless state (with equal components) for both I and A fields to
know that any previous transmission has ended, and
that the network interface is clear to send. If the I field contains a direction vector (with unequal components)
than it is busy.

Since the send \( N_+ \) and receive \( N_- \) registers of a
network interface are connected only by their being part of the network interface itself, the interface needs
to promise the circumstances or preconditions under which the link would be held up to wait for acceptance of a delivered packet, or whether some complicating buffering would be added that admits only partial delivery. The network interface needs to promise these
details as part of its self-specification.

Fig. 14: The simplest kind of exchange is the reflection of a
‘hot potato’ token between the end points of the link, like a
photon reflecting back and forth, ‘treading water’ and going
nowhere. At each end, there is a parity reversal represented
by the complement operation.

Fig. 15: Left to right transmission: In order to send a
message the ‘treading water’ phase needs to be broken by
an intentional boundary condition imposed at one of the
ends of the link. The exchange of a message, which may
be compared to figure 18 from left to right breaks thus from
the directionless tick-tack phase.

Fig. 16: Right to left transmission: In order to send a
message the ‘treading water’ phase needs to be broken by
an intentional boundary condition imposed at one of the
ends of the link. The exchange of a message, which may
be compared to figure 20 from left to right breaks thus from
the directionless tick-tack phase.

Fig. 17: Schematic L2R or A2B transfer, with interior states
of endpoint agents indicated.

Fig. 18: A left to right transfer, with injection of a packet
and acknowledgment, between pendulum phases [15].
Fig. 19: A left to right transfer, with non-accepted payload, returning NACK instead of TACK.

Fig. 20: A right to left transfer, with switch from pendulum to transfer phase.