A Morphogenesis Perspective on Deterministic Communication Networks: Time to Overcome the Positional Information Paradigm? †

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Abstract: Reconciling determinism with adaptability and resilience in the design of complex distributed system is a difficult task. In this paper, we argue that theoretical biology, especially biosemiotics and morphogenesis, gives a new perspective into this problem and presents us with new concepts that have been barely studied in the distributed systems literature. Current solutions for real-time systems are based on two simple assumptions, Positional Information and the B-series Time Code, which are only a small portion of the mechanisms used by living organisms. Investigating the application of alternative concepts on deterministic communication systems, such as inter-agential time (the E-series Time Code) and reaction–diffusion mechanisms, represents a promising path forward.

Keywords: real-time communication; scheduling; biosemiotics; morphogenesis

1. Introduction: Why Morphogenesis and Determinism?

Many crucial services, such as transportation, healthcare, manufacturing, energy, etc., depend nowadays on very complex distributed computing systems. This complexity is driven by their large size and heterogeneity, their dynamic operation in unknown/uncertain conditions, and their criticality. The developers of such distributed systems face the challenge of reconciling predictability and flexibility in their designs, to achieve determinism together with adaptability and resilience [1]. We consider that a system is deterministic if its temporal behavior can be predicted with great accuracy [2,3].

Both scientists and practitioners have turned towards natural computing as an inspiration for taming complexity. Methods, such as neural networks, swarm-based algorithms, and evolutionary algorithms (e.g., genetic algorithms), are commonly applied [4]. These methods normally address adaptability and resilience, but determinism has not received the same attention; maybe because real-time systems had proper tools and abstractions to guarantee predictability using traditional computing. Despite that, many researchers noted that traditional techniques for real-time communication do not scale well and are not sufficiently resilient [5,6]. One reason is the heavy computation required for analyzing and guaranteeing schedulability in uncertain/faulty conditions, which leads to reconfiguration solutions that are either fast but non-exhaustive or exhaustive but too slow [7,8].

We believe that a more profound revision of the architectural principles of real-time communication networks is required in order to build systems that can satisfy both determinism and resilience in efficient ways. Based on our experience, a deeper study of two areas of theoretical biology, morphogenesis and biosemiotics, helps to understand some limitations of the current approaches and can also lead towards novel design strategies.

The main operation for ensuring temporal determinism over a network is scheduling [9], which is a method to arrange periodical transmission actions over a regular temporal grid, the global clock. Considering that, it is not surprising that the study of pattern formation and
segmentation (somitogenesis) in living organisms [10] sheds light on possible alternative methods to create predictable communication/computation patterns between computers.

At present, the main challenge in the study of morphogenesis is to identify and understand the role of the morphogens: the substances responsible for activation and inhibition of the patterns [11]. Our claim is that once a general theoretical framework exists for representing these relations, along the lines of the one proposed in [10], computer scientists will be able to embody such interactions in scalable and efficient low-level mechanisms. This generative approach makes determinism an emergent property of the system and not an aprioristic condition on which further determinism is built. This point will be clarified in Section 2.

In addition to the study of morphogenesis, it is important to look at the notion of time and synchronicity in nature, and to understand how it is dynamically constructed by interacting agents. Some experts in biosemiotics have theorized about the different types of relations (or Time Codes) that living beings construct [12]. The study of these relations reveals that traditional scheduling solutions only operate with a very fundamental concept of time, the B-series, also known as the third person observer. We believe that this limitation lies at the core of many of the adaptability problems faced by large-scale real-time systems, such as the inability to merge schedules coming from different clock domains.

2. Time-Triggered Communication under a Morphogenesis Lens

To illustrate our claims, let us focus on the Time-Triggered (TT) paradigm, which is one of the most widespread approaches for real-time communication [2]. TT is fundamentally a static way to share communication bandwidth between nodes, such that a predefined response time with little jitter is enforced [13]. We note that the TT paradigm is embodied at three different levels of abstraction, by application of three structures:

- Global clock > Time slots > Schedules

The Global clock constitutes the fundamental signal that governs the rest of the mechanisms. It is monotonically increasing and the axis on which the other structures are built. The second structure is a division of time in Time slots, also static and performed a priori. This division uses the Positional Information paradigm [14,15], because time instants are grouped as slots according to a predefined (fixed) function over the global clock. Thus, the change of slot is a function of the gradient of the global clock “function” over time.

The schedules are the third structure. Their goal is to establish a pattern of transmission and reception windows over the links used by the nodes, such that communication can happen end to end with a predefined delay; as long as the nodes follow the schedules and their time slots (local to each node, but based on the global clock) are well synchronized.

The parallelism between TT and segmentation in morphogenesis is that the scheduled time windows can be seen as the segments (or somites) and their assignment to a certain message can be interpreted as cell functional differentiation. The generation/synthesis of such coherent TT schedules is normally performed offline using constraint programming or SMT solvers. The resulting schedules are static and need to be regenerated online in case of a system change or a failure. This differs radically from segmentation in living organisms, which is not a centralized process and is very adaptive [10]. As A. Turing noted in the 1950s, pattern formation can be generated by decentralized reaction–diffusion patterns [16].

The TT scheduling problem epitomizes the dichotomy between symbolic and embodied representations of a system, since it works as follows: a real problem is abstracted into a symbolic representation (the schedule synthesis problem) which is solved symbolically via central computation. The symbolic solution, i.e., the schedules, are transformed, or embodied, into a real implementation by reconfiguration of the system, normally with individual scheduling tables stored in each node’s memory.

However, as noted before, this way of working is correct only if there is high-fidelity between the real system and its symbolic representation. Fidelity guarantees that once a solution is calculated in abstracto, its deployment on the real system will exhibit the expected behavior [3]. Small fidelity errors can normally be tolerated, but any significant
deviation between the real system and its symbolic representation may yield the solution incorrect or useless. This happens, for example, if a link failure occurs. Then, the part of the schedules corresponding to that link becomes unfeasible, leading to a deadline violation.

Importantly, this also happens when the other structures (the clock and the time slots) are defective. For instance, if the local clocks drift away from the global clock or when a system is obtained as the union of two subsystems whose schedules cannot be merged because their time slots are incoherent with each other. The only solution that TT offers to prevent these issues is to enforce very tight and robust clock synchronization, by means of frequent synchronization and use of redundancy, or to reboot the system.

We already proposed a mechanism for self-healing TT schedules based on impromptu generation of portions of schedules, or hot-patching [7]. However, to devise novel mechanisms that could re-generate the structures at deeper levels, such as the time slots, it is crucial to understand how to build synchronization in a generative manner. For that, we turn to biosemiotics and the study of meaning in living organisms.

Nomura et al. [12] describe four different interpretations of time in living systems, two of which are relevant to our problem. The B-series time code, also called the third-person observer, is objective and does not assume the participation of the agent using the time. For TT, both the Global clock and the Time slots are B-series. An alternative to this is the E-series time code, or second-person negotiator, in which each agent participates in the co-creation of the temporal structure by means of intersubjective punctuation. For real-time communication, this means that transmission/reception actions should become part of the time generation process, as signs that not only carry information but also embody intention.

3. Conclusions

Computer science and theoretical biology have a long history of mutual influence. We uncovered the relation between deterministic communication systems and pattern formation in living organisms, and highlighted some aspects deserving further investigation.

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