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Notes on Asynchronous Systems in Nature, Life and Technologies

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Abstract

In this review, we consider a system of a finite number of entities (agents) possibly interacting within the system and changing their states controlled by time, a system parameter defined for the system's operation. The changes of the state are perceived synchronous for all the agents when there is a mechanism controlling the different agents by forcing them to change their status simultaneously. This system parameter of time is issued to all agents by a control entity. However, the utilization of such a control mechanism is associated with an additional cost of system functioning. The advantages of asynchronous control are coming from replacing global control with the local interaction among the agents. We present examples of asynchronous architectures illustrating their effect. Also is stated the effect of the so-called orthogonal systems which are preferred when their design and utilization is feasible.

This subject is discussed in the context of different definitions of time as a control parameter.

There is

A time for everything, and

A season for every activity under the heavens:

A time to be born and a time to die,

A time to plant and a time to uproot, …

Ecclesiastes [1]

Keywords: Asynchronous; Radiofrequency energy; Solar time; Circadian rhythms; Polychronous vs. Monochronous

Abbreviations: NIST: National Institute of Standard and Technology;

Introduction

The notion of time has been in the foundation of the most important concepts of human experience. The discussion on synchronization of interacting agents and the way how an asynchronous control can excel the system's performance is important to start with a brief review of different notions of time in various human experiences.

Time in control of individual and social lives

As it is said in the Ecclesiastes [] there are some periods (times) of human life which can be taken as given:

There is

i. a time to weep and a time to laugh,

ii. a time to mourn and a time to dance,

iii. a time to scatter stones and a time to gather them, …

The time definition above concerns the fundamental principles of human existence. We focus here on time as a parameter controlling the state of a system as a whole and its individual entities.

The role of time in human's individual and societal lives

The concept of time is perceived to be universally and sometimes inexplicitly presented in phenomena, designs and models. Immanuel Kant [2] believed that time does not exist beyond human mind. This notion turns out to come very close to what is perceived about time today which is that time is based on the brain ability to memorize events. Our perception of time comes with our ability to memorize as we go through life experiences. One of such aspects of our everyday amusement is our lives with and within big systems of multiple actors capable of pursuing various and sometimes contradictory objectives. They are performing under local governing rules. Moreover, in many cases such systems work more efficiently when compared with the systems being under some governing control. One of such well popularized examples concerns the approved efficiency of the market economy as compared with the one controlled by the state.

Asynchronous

Another example taken from the computing technologies arena provides the view of the complex operating systems acting asynchronously. The Amazon Chief Technology Officer Dr. Werner Vogels has been one of the strong proponents of the asynchronous computing architecture [3].

Time is a Social Construct [4-6]

NIST Installation

The rigid time that governs most of the societal activities and individual lives comes from the installation at National Institute of Standard and Technology (NIST) [7]. It is the 21-clock ensemble NIST uses to generate the official time. The hydrogen atoms are excited using radiofrequency energy and then sent into a chamber. Once inside, they decay, emitting a specific frequency of light. This is the version of time the government wants to authorize. This version of time runs our lives and all activities. It can be used for synchronization of traveling facilities, financial transactions, especially those around the globe which should have the timestamps internationally accepted.

Solar Time

During the most of human history people relied on astronomical observations to synchronize their activities. Solar time is based on a calculation of the passage of time based on the position of the Sun in the sky. The unit of solar time is the day. Obviously, this is not acceptable metric in most technology dependent environments.

Time is a Human Affair

As it was mentioned above, time as a commonly accepted definition is a result of neurons firing in the brain. The result is the memories formed in hypothalamus. The memories are used to compare the events and thus defining the metrics of time. Human physiology is affected by the speed of human interaction with the environment. One of such examples concerns the saccadic action of the mechanism of vision. Its analysis can be found in [8]. The perception of time is based on human's brain activities, an analysis of this phenomenon was attempted in [4-6].

Circadian Rhythms [8,9]

Biological clocks are organisms' natural timing devices, regulating the cycle of circadian rhythms. 'Time cells' in the brain are critical for complex learning, study shows. A sense of time is fundamental to how we understand, recall, and interact with the world. Tasks ranging from holding a conversation to driving a car require us to remember and perceive how long things take-a complex but largely unconscious calculation running constantly beneath the surface of our thoughts. But time cells aren't just a simple clock, the researchers found-as animals learn to distinguish between differently timed events, the pattern of time cell activity changes to represent each pattern of events differently. The discovery could ultimately aid in early detection of neurodegenerative diseases, such as Alzheimer's, that affect the sense of time.

Episodic memory requires encoding the temporal structure of experience and relies on brain circuits in the medial temporal lobe, including the medial entorhinal cortex (MEC). Recent studies have identified MEC 'time cells', which fire at specific moments during interval timing tasks, collectively tiling the entire timing period. It has been hypothesized that MEC time cells could provide temporal information necessary for episodic memories, yet it remains unknown whether they display learning dynamics required for encoding different temporal contexts.

Polychronous vs. Monochronous

We claim that it is important to differentiate between the systems of entities having the comparable time scales of operation (that is monochronous systems) and those ones where the essential agents operate with different speeds (polychronous systems). In a typical system, all the agents can perform, simultaneously, a specific action as their modus operandi requires, then exchange their outputs and continue with the same period. In reality, many natural and engineered systems have interacting entities of different performance.

In most real life and engineered models, their actions, as described above, converge to some stationery states after which the actions stopped.

What will happen in polychronous systems? Should the fast operating agents (OPTION A) wait for their slower neighbors to deliver or they should continue (OPTION B) to operate even with the obsolete external data? Option A requires system synchronization. It seems to be able to deliver the correct final distribution but in expense of overall productivity. Option B means that the overall system does not need synchronization although being able to deliver the correct system output and even faster than the synchronized one.

The following statement is proven to be true within various realms in nature, human physiology and mental process. Essentially, the systems, commonly, operate as asynchronous polychromous aggregate in the environment where synchronization is available. The combination of the both modus of operandi is a typical system organization.

The World is Asynchronous

The birds formation is an example. Out of birds disseminated clouds to progressively more condensed and regularly formed geometrical formations as it is shown below (Figure 1).

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Figure 1: Thorax X Ray films.

Example of a synchronous (OPTION A) vs. asynchronous model (OPTION B) of flying birds. We consider a simple model of agents finding the equally distant locations between two leaders staying at the same position. At every step in time each of the agents reads the current positions of its neighbors and positions itself in the middle between the neighbors at the moment. The process converges to the stable equidistant positions of agents without any synchronization.

An illustration of this asynchronous process is presented below. The example here is analyzed under an assumption of monochromic action which means that all the agents act with quite comparable speeds. Still, each agent can perform on its own time and contact the other agents as the agent's algorithm would require.

No external clock and synchronization would be used and needed (Figure 2).

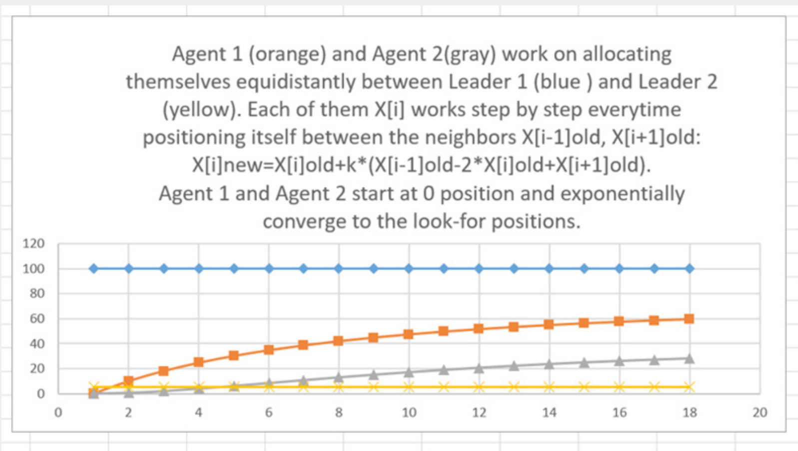

Figure 2.

The next illustration represents the polychromic case when the time scales of individual agents can be significantly different. As it shown below the conversion occurs in this case as well (Figure 3).

More specific analysis and discussion can be found in Appendix. In various applications and environments, the same conclusion can be made: in multi-agent systems including the human society the unsupervised, asynchronous interaction can provide more efficiency. Even when synchronous operations may be needed, the best modus operandi of any system is expected to be an asynchronous one in the majority of its functions.

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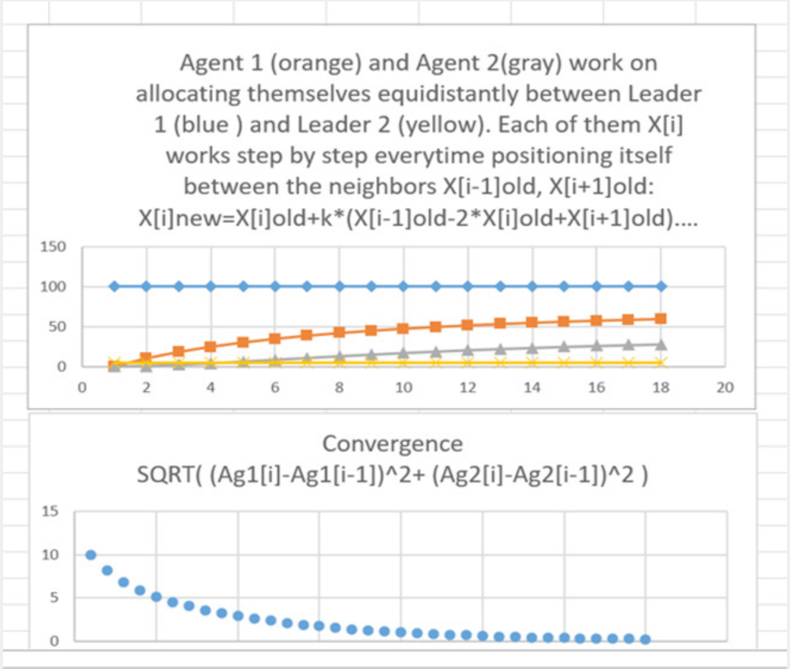

Figure 3.

Asinchrony of Operating systems

The heart and brain of any computer-based installation is its Operating System (OS). In his recent comments on this subject by Dr. Vogels [3] the following question was raised:

What is Synchrony? Event Driven Architecture – all events should be synchronized (?) Should be checked - No blocks on any resources (?) Controlled Concurrency + Controlled Parallelism. That is meant to be a significant inability to synchronize the above processes.

Synchrony is an illusion!

Instead: Asynchrony + Parallel - present the need for proper organization of distributed asynchronous processes - They are controlled locally but the effect is global. The interaction is based on interrupts as it is the Event driven systems. A number of OS's in the 90-s. Windows-NT - the first one used asynchronous communication or interaction with devices. Only in 2019, io-turing was introduced in Linux to provide real asynchrony. Synchrony leads to tightly coupled systems. "If anything fails, the whole system probably fails."

This is an evolvable architecture. It is a loosely coupled system. The principles of the system design based on asynchronous control were utilized by the Amazon AWS Application Composer. Based on the principle of asynchronous control to a simplified generating deployment ready configuration was presented by Amazon's AWS Application Composer.

Orthogonality of Locally Controlled Asynchronous Systems

Since the asynchronous multi-agent systems operate on direct communication among the system entities the transparency of their interaction becomes crucial when it goes about providing minimum performing losses in one-to-one communication.

This issue has been discussed in the context of so called orthogonality of the system under consideration. As it is shown in [5], the system is considered orthogonal if all agents can obtain the access to the needed resources with minimal losses in time. We can say that the simple model of the flying birds considered above sub orthogonal since each bird can see the positions of the neighbors without any delays from the system. The main issue here is provision of transparency of all resources

(1) $x_i(t)$: a characteristic function of the i-th agent demand of system resources (call to environment).

$$x_i(t) = \begin{cases} 0, & \text{no need for system service} \\ 1, & \text{agent sets demand for service} \end{cases}$$

(2) $y_i(t)$: a characteristic function of the environment to serve the i-th agent's demand if such demand is set.

$$y_i(t) = \begin{cases} 0, & \text{system transparent to agent} \\ 1, & \text{service is not available} \end{cases}$$

needed to

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Orthogonality metric, μ, is defined as the average value of a dot product computed over the time interval, $t \in [0, T]$:

$$\mu = \|X(t), Y(t)\| = \frac{1}{nT}\sum_{i=1}^{n}\int_0^T X_i(\tau)Y_i(\tau)d\tau \qquad (1)$$

$(0 \le \mu \le 1.0)$.

In addition to orthogonality metric, we consider the *transparency*, θ, of multi-agent system as a complement of orthogonality metric to unity:

$$\theta = 1 - \mu$$

Maximal transparency of the multi-agent system equal to 1.0 means that all resources of the system transparent to any of its agent at any moment.

The design of orthogonal asynchronous systems will become available based on the provided principles.

Conclusion

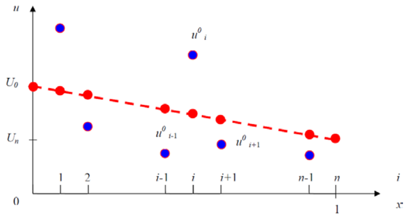
In various applications and environments, the same conclusion can be made: in multi-agent systems including the human society, natural and engineering objects the unsupervised, asynchronous interaction can provide more efficiency. Even when synchronous operations may be needed, the best modus operandi of any system is expected to be an asynchronous one in the majority of its functions. Here we discussed definitions of time as a control parameter in both synchronous and asynchronous systems in different environments. A discussion of advantages and possible issues when a system designed as an asynchronous is presented here hopefully will allow to continue this discussion further. It is expected that the analysis of asynchronous implementation will continue to provide some specific details of systems implementation.

Appendix. A cluster of reflex agents locally controlled

Consider a cluster of n+1 reflex agents ai, i = 0, 1,..., n forming a linear chain. Each agent is equipped with a billboard where it posts, occasionally, a numerical message ui and with two sensors for reading the messages ui-1, ui+1 from the billboards of the agent's closest neighbors.

Agent ai (0<i<n) performs the following action: once either ui-1 or ui+1 changes, the agents posts their mean value as a new message ui.

At some moment, agents a0 and an set messages U0 and U1 and never change them again.



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1

For the purpose of the further discussion, the agents' indexes are mapped onto a continuous unit x-interval:
$(0, 1, \ldots, i, \ldots, n) \rightarrow (x = 0, 1/n, \ldots, i/n, \ldots, 1)$

Thus, $n+1$ agents are uniformly distributed over the unit x-interval (the distance between any two adjacent agents is $\Delta x = 1/n$). The values of initial messages are shown in blue, and the steady state solutions in red.

The environment here is a set of agents' messages. It is observable, stochastic, sequential, dynamic, multi-agent, and, arguably, discrete (although the numerical messages are defined over a continuous domain, the environment should be considered as discrete since the set of messages is discrete unlike in cases when environment itself is continuum).

An agent deals with a random stream of messages that should be a converging sequence of numbers with a linear distribution of steady-state messages as illustrated in the graph above. To discuss these issues we consider the following mathematical model of the multi-agent cluster.
Agents perform their actions in discrete moments enumerated with $k = 0, 1, \ldots$ when one or both observed messages change. Using k as a superscript index the following can be written as the model of the agent's a_i action (the agent's message is changed to the mean values of the neighbors' messages set up at the previous time step):

$$u_i^{k+1} = (u_{i-1}^k + u_{i+1}^k)/2 . \qquad (1)$$

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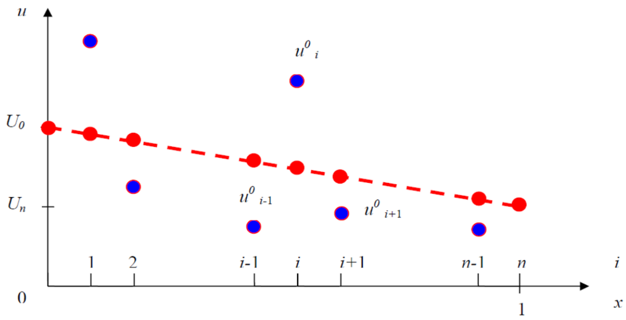

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$$u_{i-1}^k - 2u_i^{k+1} + u_{i+1}^k = 0 .$$

Assuming that this process is converging:

$$u_i^{k+1} \approx u_i^k ,$$

one can conclude that the steady-state solution can be presented as

$$u_{i-1} - 2u_i + u_{i+1} = 0 \qquad (2)$$

(note that the superscript k is not needed here).
After multiplying (2) through by $1/(\Delta x)^2$ the following steady-state multi-agent model is obtained as a set of simultaneous finite difference equations:

$$\left(\frac{u_{i+1} - u_i}{\Delta x} - \frac{u_i - u_{i-1}}{\Delta x} \right) \frac{1}{\Delta x} = 0 , \quad i = 1, 2, \ldots, n-1,$$
$$u_0 = U_0, \qquad (3)$$
$$u_n = U_1.$$

Instead of solving linear algebraic equations (3) which requires working through the matrix operations to obtain the solution in general form, we can consider a continuous analog of this discrete model by assuming that there is an increasingly large number of agents over the unit x-interval while Δx approaches 0.

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$$\lim_{\Delta x\to 0}\left[\left(\lim_{\Delta x\to 0}\frac{u_{i+1}-u_i}{\Delta x}-\lim_{\Delta x\to 0}\frac{u_i-u_{i-1}}{\Delta x}\right)\frac{1}{\Delta x}\right]=0$$

$$\Rightarrow \lim_{\Delta x\to 0}\left[\left(\left.\frac{\partial u}{\partial x}\right|_{x=x_i}-\left.\frac{\partial u}{\partial x}\right|_{x=x_{i-1}}\right)\frac{1}{\Delta x}\right]=0$$

$$\Rightarrow \frac{\partial^2 u}{\partial x^2}=0,\quad u=u(x),\quad x\in[0,1]. \qquad (4)$$

Now, we have to solve the equation (4) with boundary conditions:
$u(0) = U_0$,
$u(1) = U_1$. (5)
We obtain the solution by integrating (4) twice:
$u(x) = A\,x + B$
Constants A and B can be found from the boundary conditions:
$U_0 = B$,
$U_1 = A + U_0$,
or,
$A = U_1 - U_0$.
Thus, the steady-state distribution of the agents' messages is indeed a linear function of x:

$$u(x) = (U_1 - U_0)\,x + U_0, \qquad x\in[0,1], \qquad (6)$$

or index i:

$$u_i = (U_1 - U_0)\,(i/n) + U_0, \qquad i\in[0,n]. \qquad (7)$$

(Note that (7) is obtained directly from (6) by substituting x with i/n and denoting $u(i/n)$ as u_i.)

Having established that the steady-state distribution does exist we now should discuss the issue of achievability of the steady state which is *a priori* not obvious.
We can do this by creating a non-stationary model of the agents behavior by introducing time.
Consider the equation:

$$\frac{u_i^{k+1}-u_i^k}{\Delta t}=\frac{1}{2}\left(\frac{u_{i-1}^k-2u_i^k+u_{i+1}^k}{\Delta x^2}\right). \qquad (8)$$

Here, Δx is the same constant as above, and Δt represents a time step between two consequent actions of agent a_i.
Equation (8) is identical to (1) provided that

$$\frac{\Delta t}{2\Delta x^2}=1. \qquad (9)$$

(Note that this is the upper bound of the *stability* condition known in the numerical analysis.)

Similarly to steps before we consider a continuous model in time and space assuming that the agents' density grows infinitely while the time step becomes infinitesimal.

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$$\lim_{\Delta t\to 0}\left(\frac{u_i^{k+1}-u_i^k}{\Delta t}\right)=\frac{1}{2}\lim_{\Delta x\to 0}\left(\frac{u_{i-1}^k-2u_i^k+u_{i+1}^k}{\Delta x^2}\right)$$

$$\Rightarrow \frac{\partial u}{\partial t}=\frac{1}{2}\frac{\partial^2 u}{\partial x^2}. \qquad (10)$$

Here, $u = u(x, t)$. (10) is a well known partial differential equation – a one-dimensional Fourier (heat transfer) equation which is, in order to have a unique solution, complemented with boundary conditions (as in (3)) and a given initial distribution of messages, $V(x) = u(x, 0)$. Assuming homogeneous boundary conditions $U_0 = 0$ and $U_1 = 0$ (it is justified because we are interested only in non-stationary solution) the solution of (10) can be found in the following form (by using the Fourier method of separation of variables):

$$u(x,t)=\sum_{n=0}^{\infty} c_n e^{-(n\pi)^2 t/2}\sin n\pi x. \qquad (11)$$

Here c_n are coefficients in the Fourier series expansion of the initial distribution $V(x)$. For the complete coverage of this method you are referred to any text book on the advanced mathematics or partial differential equations, however, it is easy to find a solution in some simple representative case such as for the initial condition:

$$V(x) = \sin(n\pi x). \qquad (12)$$

The following function provides the solution of (10):

$$u(x,t)=e^{-\pi^2 t/2}\sin \pi x. \qquad (13)$$

(13) satisfies the homogeneous boundary conditions, the given initial distribution (12) t=0, and, finally, (10) since the first derivative of (13) with respect of t:

$$u_t(x,t)=-\pi^2(e^{-\pi^2 t/2}\sin \pi x)/2$$

and the second derivative of (13) with respect of x:

$$u_{xx}(x,t)=-\pi^2(e^{-\pi^2 t/2}\sin \pi x)$$

after being plugged into (10) make this equation identity. It is obvious that $u(x,t)$ is vanishing since it is an exponential function with a negative exponent.

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Conclusion. The messages produced by the agents converge to the steady state distribution regardless of the boundary conditions and initial distribution.

The above discussion has a flow: it does not reflect the fact that each of the agents is autonomous and, therefore, changes the messages as though they are random numbers. Although the conclusion made above is correct the proof of it should it be made by using more rigorous technique. Such technique has been developed in form of methods of *asynchronous and chaotic iterations*. The appropriate discussion goes beyond the scope of these notes (some references in the context of the *method of orthogonality* can be found in [1]).

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