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MODELING HUMAN BEHAVIOR – AN (ID)ENTITY CRISIS?

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ABSTRACT

Agent-based modeling (ABM) has gained great popularity in recent years, especially in application areas where human behavior is important, because it opens up the possibility of capturing such behavior in great detail. Hybrid models which combine ABM with discrete-event simulation (DES) are particularly appealing in service industry applications. However in this paper we argue that many of the so-called distinctions between agents in an ABM and entities in a DES are artificial, and we describe several DES models which use standard entities to represent agent-like behaviors.

1 INTRODUCTION

1.1 Background

In March 2010, the UK Operational Research Society Simulation Workshop SW10 included a panel discussion entitled '*Discrete-event simulation is dead, long live agent-based simulation*!'. This discussion was subsequently published in the Journal of Simulation (Siebers et al. 2010), and there was a similar panel discussion, extended to cross-paradigm modelling, at the 2011 Winter Simulation Conference (Heath et al., 2011).

Within the mainstream Operations Research community, there has undoubtedly been much interest in recent years in the use of agent-based modeling (ABM). The motivation for the present paper originates from a second paper in the Journal of Simulation (Brailsford 2014), written in response to Siebers et al (2010), in which I argue – admittedly as a devil's advocate – that many of the cited benefits of agent-based modeling can be achieved through the use of a traditional DES approach. In the current paper, I argue that many of the distinctions between agents in an ABM and entities in a DES are artificial, and that many hybrid models which use both ABM and DES could equally well just use one or the other. Moreover, these hybrid models could be more easily developed in a single paradigm. These arguments are illustrated by several examples where DES has been used successfully to tackle 'ABM-type' problems.

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The paper assumes that the reader is reasonably familiar with the basics of both ABM and DES. The latter can be taken for granted for the WSC readership, but readers who require an introduction to ABM are referred to Macal and North (2010).

1.2 History

The purpose of this paper is obviously not to chart the history of either ABM or DES, which would be the work of a lifetime, but to try to understand some of the differences between them: a topic to which their disciplinary ancestry is relevant. The origins of agent-based modelling (ABM) date back to the 1940's and the work of John von Neumann, which led to the concepts of cellular automata and the resulting famous checkerboard models like Conway's Game of Life (Gardner 1970) and Schelling's model of segregation (Schelling 1972). However it was only with the advent of computing that ABM began to come into its own. Initially it was mainly computer scientists who were interested in ABM and its use for "artificial life": for example Craig Reynolds, who developed the "boids" model of flocking behavior in birds (Reynolds 1986). However by the 1990's social scientists had realized its potential benefits and research groups such as the Santa Fe Institute and the Brookings Institute were beginning to explore the use of ABM for modelling human behavior (Epstein and Axtell 1996; Macal 2009).

Similarly, the history of discrete-event simulation (DES) largely mirrors the history of computing. While "analog equivalents" of DES were used in manufacturing (in the form of scale models of factory layouts) it was only really when desktop computers came along that DES became widely accessible. Interestingly, DES has traditionally fallen predominantly into the domain of operations research (OR), although of course there are strong links with computer science in terms of the development of software and algorithms.

1.3 Modeling human behavior

My personal interest in modeling human behavior dates back about 12 years, when I first began to explore the possibility of including patient behavior in healthcare models, my main field of interest. In such models, the entities are usually patients and patients do not always behave rationally or predictably. We all know smoking is bad for us, and we all know we should eat less, drink less alcohol and take more exercise, yet we continue to behave in sub-optimal or even irrational ways. Modeling human behavior in healthcare systems is particularly important as it affects clinical outcomes. At the time I was a fairly experienced user of DES, but ABM was not really "on my radar" until I discovered the work of Bernd Schmidt (Schmidt 2000). Schmidt had developed an agent architecture entitled PECS (physical, emotional, cognitive and social) which – in common with many such frameworks, I have since discovered – was entirely theoretical. Schmidt was keen to find a real-world application and so together we developed a DES model for diabetic retinopathy screening (Brailsford and Schmidt 2003). Retinopathy is a fairly common complication of diabetes which can lead to blindness, but can be detected and treated before the patient is aware of any symptoms. Our model was a traditional DES but it contained a formula based on the PECS characteristics which calculated an individual patient's probability of attendance for screening, using data from the health psychology literature on screening behavior. On reflection, this arguably makes it a hybrid model!

Of course human behavior is not only important in healthcare systems, but in any system where human beings make decisions or perform activities. Human beings can get tired, cross or inattentive: they can be lazy, overenthusiastic or forgetful. The possibility of modeling such factors explicitly allows the possibility of modeling scenarios and interventions to mitigate against them. Any kind of service industry will involve human "participants" whose behavior can affect the performance of the system. Even manufacturing industry, where many systems are automated, still involves humans at some point.

2 EMERGENCE

One of the key features of ABM which marks it out from DES is its ability to capture *emergence*. Emergence is a property of a system which arises from characteristics of the individuals within the system, yet is not possessed by any of the individuals themselves. There are many examples of emergence: Brailsford (2014) quotes a simple example of a grid composed of rows of black and white dots, where the individual dots only have two properties (their location and their color) but the lines which emerge are a system property, possessed by the whole set of dots. Schelling's segregation and Reynolds' flocking boids also illustrate system properties. The individuals on Schelling's checkerboard need have only a mild preference for being the same color as their neighbors, yet that is sufficient to produce marked segregation effects over time. All the individual boids have to do is follow a few extremely simple rules, yet they produce complex and beautiful flocking patterns.

Another example of emergence is congestion in traffic flow. Imagine a car race around a circular track, where each car has only one rule: it must simply follow the car in front without overtaking. As long as all the cars drive at a constant speed, say 60 mph, the system will be stable. However our intuition from queuing theory tells us that if we introduce a small amount of variability around the average speed of 60 mph for each car, we will gradually begin to observe queues building up. An interesting observation when this race is modeled (or a real race observed in practice, such as Formula 1) is that the queues build up in the opposite direction of flow to the cars! A queue is not a property of any individual car; it is an emergent system property. It is easy to visualize this effect in any of the nice agent-based software tools available today. Could this car race be modelled in DES?

3 AGENTS AND ENTITIES

3.1 Agents

Agents are the individuals which exist inside an ABM. They normally, but not necessarily, exist within an environment, which can be spatial (anything from a checkerboard up to a geographical map of a specific region) or aspatial (such as a social network). Agents are autonomous, meaning that they can each act independently. Agents have memory, and can remember (perfectly or imperfectly) what has happened to them in the past and learn from it, adapting their responses and behavior in future. They can pass messages to each other; they can also pass messages to the environment, and receive messages back from it. Their behavior is determined by rules which can range from simple "if .. then" conditions, through to highly complex stochastic learning algorithms and abstract representations of the relationships between system states and the individual agent's perceptions of them. The crucial point is that the rules governing this behavior still have to be coded into the program by the modeler, even though of course, the modeler does not know in advance what system behavior will ultimately be produced. After all, that is why simulation is needed.

3.2 Entities

Entities are the individuals which exist inside a DES. They normally, but not necessarily, exist within an environment, which can be spatial (e.g. a factory layout or an airport terminal) or aspatial (e.g. a disease progression model, in which individuals pass through different stages of a disease). Entities do not normally pass messages to each other, although in principle they could be programmed to do so, but they do receive messages from the environment and pass messages back to it. At its very simplest, this could be messages like "This queue is full – please try the next queue in the list", or "I have top priority, please place me at the front of the queue". The behavior of entities, i.e. their progression through the system, is handled in slightly different ways depending whether an event-based, activity-based or process-based perspective is being used by the DES engine, but conceptually this behavior is determined by rules which can range from simple "if- then" conditions, through to highly complex stochastic algorithms and abstract representations of the relationships between system states and the individual entity's properties. These rules have to be coded into the program by the modeler, even though of course, the modeler does not know in advance what system behavior will ultimately be produced. After all, that is why simulation is needed.

3.3 So what's the difference?

Agents and entities appear on the face of it to be remarkably similar. An entity and an agent are both distinct individuals and can both be given unique characteristics or "labels" which mark them out from all the others. Agents can pass signals or messages to other agents, whereas entities do not generally do this. However, there have been many DES models where entities communicate with each other, such as models for infectious diseases where an infected entity transmits the disease to a susceptible (uninfected) entity. For example, Rauner et al (2005) present a DES model for mother-to-child HIV infection, in which the entities are mothers and babies, and the process of transmitting the virus from mother to baby is modelled as a standard DES activity in which both mother and baby participate, and after which the HIV status of the baby changes from negative to positive.

Agents can learn and adapt their responses over time, whereas entities generally do not do this, but there is no technical or conceptual reason why they should not. Consider the following very simple example, developed in the software Simul8 (www.simul8.com), depicted in Figure 1 below. Customers walking into a bar are randomly assigned an integer characteristic called "desired number of drinks" on entry and this number is decremented each time the customer buys a drink. A rule coded into the model checks the value of this variable whenever the customer is deciding whether to buy another drink, and when it equals zero, the customer exits.

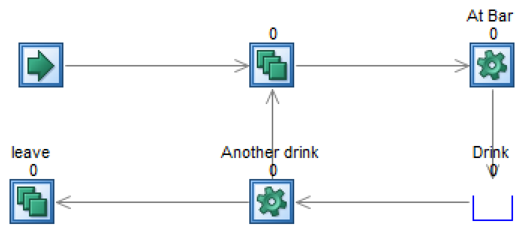

Figure 1. Simul8 implementation of the bar

A classic DES … yet it is easy to see how this model could be made more realistic (and ABM-like) by giving the customer entities additional characteristics, e.g. "tolerance for alcohol", "susceptibility to peer pressure" or "willpower", which could be affected either deterministically or stochastically by system or individual states: the number of other people in the bar, the type of drink consumed, and so on. Such rules could simply be coded into the "Another drink" activity. One could then argue that the customer entity is learning the effects of alcohol, and adapting their behaviour.

Typically, the environment in which DES entities live is a queuing system, but it does not necessarily have to be a physical queuing system. The HIV model developed by Rauner et al (2005) is conceptually a queuing system, but there are no actual queues in it. Equally, agents in an ABM can also live in queuing systems. Both ABM and DES models can contain environments for which the graphical representation is very realistic, like watching a movie, as the software vendors say.

3.4 The (id)entity crisis

It is easy to see why ABM has attracted both computer scientists and social scientists. Emergence and complexity are fascinating concepts in their own right; for programmers, agent-based models are fun to develop and can have compelling and often beautiful visualizations. For social scientists, the ability to create artificial societies and conduct social experiments "in silico" is clearly a very attractive option, compared with the challenges, both practical and ethical, of conducting such experiments in the real world. Surely, the Schelling model tells us something subtle and profound about racial or religious discrimination among people who, as individuals, would claim to be liberal-minded and tolerant.

However it is perhaps less easy to see why OR people would be interested. OR is primarily concerned with problem-solving in a real-world setting, and (with the notable exception of pedestrian flow models, which are rather a special case) there have been relatively few practical applications of ABM to date, despite increasing academic interest over the past decade. In the SW10 panel discussion (Siebers et al. 2010), one of the panelists, Jeremy Garnett, summed this up perfectly in his comments about the work of the Santa Fe Institute in the 1990s. Garnett says this work included *"... some of the best-known applications of ABS, such as the 'game of life', 'flocking', slime mould and Schelling segregation. These examples are of great academic interest; in particular, they seem to point towards universal, fundamental theories of nature. However, they are very theoretical, and none of them are based on actual implementations. Therefore, they are of limited relevance to the practice of OR; OR is not generally concerned with uncovering fundamental theories of nature".* (Siebers et al. 2010)

In my response (Brailsford 2014) I went on to say: "*Indeed not:.. while fundamental theories of nature are of great interest to physicists and sociologists, most practically minded operational researchers start with a real-world problem and then try to find the best pragmatic way to solve it. In my opinion, until ABS is shown to be useful for this it will not be widely accepted by the OR practitioner community*." (Brailsford 2014).

The fundamental question posed in this paper is: is there really a substantive philosophical difference between agents and entities? Do we really need ABM? And in particular, do we really need hybrid ABM-DES models?

4 WHAT THE LITERATURE TELLS US

4.1 Hybrid ABS-DES models

This is a relatively new field. A Web of Science search on 5 May 2014 using the search string "hybrid agent based and discrete event" in either title, abstract or key words yielded only 49 hits, as shown in Table 1.

Table 1: Publications of hybrid ABM-DES models, from Web of Science (*First four months only)

Year		Year		Year	
2014*	3	2008	5	2002	3
2013	10	2007	3	2001	3
2012	4	2006	3	2000	0
2011	5	2005	0	1999	1
2010	4	2004	0		
2009	3	2003	2		

There appears to be a slowly increasing trend, and it is interesting to note that three of the papers from 2013 were from WSC. This year's Proceedings will contain far more: this new mini-track on Hybrid Simulation contains 21 papers. By contrast, a Google Scholar search on the same date using the same search string yielded about 4, 370 hits, although of course most of these would have just contained the search terms somewhere in the document. It is clear (from a brief scan of a small random sample from the first couple of pages listed by Google Scholar) that very few of these actually describe a hybrid ABM-DES model themselves. It is also noteworthy that most of the 49 Web of Science hits were conference papers, and most publications appeared to be theoretical rather than describing applications. This reflects the fact that this is a new field, clearly very attractive to researchers but not yet producing many models which have been applied in practice.

4.2 The challenges of hybrid modeling

The fact that this new track at WinterSim has attracted so many papers is testament to the increasing popularity of hybrid simulation modeling. Simulation practitioners have long recognized that many real-world problems do not fall neatly into the domain of one single and obvious modeling paradigm. Many researchers have worked on the issues of model choice and there are several useful frameworks in the literature for selecting a modeling paradigm: a good example from the domain of healthcare is Brennan et al. (2006). Of course there will always be an element of "when all you have is a hammer…"; it is usually quicker to use a tool with which you are familiar, even if you need to make occasional compromises on the model structure. Equally, several of the papers in this track address the technical and conceptual challenges of developing hybrid models: for example North (2014), Fakhimi et al. (2014) and Lynch et al. (2014).

Arguably, one of the major factors in recent years which has contributed to the growth of hybrid modeling has been the increasing popularity of the software tool Anylogic (www.anylogic.com). This is really the first tool which has started from an "agnostic" basis and allows the user to use DES, ABM and system dynamics (SD) all within the same environment. Many other DES tools now incorporate SD-like features, and vice versa, but they have their roots firmly within one particular paradigm. Uniquely, Anylogic embodies a philosophy in which the modeler does not have to begin by thinking "Is this a DES problem, an ABM problem or an SD problem?" but can simply mix-and-match components within the same Java-based environment and can (in principle) move seamlessly from one paradigm to the other within a single model, almost without noticing.

Other than using Anylogic, the only option for developing hybrid models involves quite a lot of coding. This can either be in a standard programming language such as C++, or an open-source ABM tool such as Repast Simphony (http://repast.sourceforge.net/) which permits the user to write additional DES code, or in one of the commercial-off-the-shelf (COTS) packages which permit a degree of cross-paradigm modeling. Anastognou et al. (2013) present a hybrid ABM-DES model for emergency medical services which was developed in Repast Simphony. This model required a great deal of expert coding, although admittedly this model was particularly complex because it was also a distributed simulation in which each individual hospital DES model, and the ambulance service ABM, ran on separate processors. Viana (2014a) compares two possible options for developing a hybrid model using COTS software, namely either using Anylogic or using two single-paradigm tools and linking them via an interface. In his case, he used an Excel interface to link a DES model developed in Simul8 with an SD model developed in Vensim (https://vensim.com/). None of these options are straightforward for the novice user and all require programming skills. Indeed, even Anylogic requires some familiarity with Java, and moreover, our experience (Brailsford et al. 2013) is that there will still be times when an experienced user of (say) DES will be frustrated by its relative lack of functionality, compared with a conventional DES package. There is a price to be paid for being "jack of all trades". Obviously, these mainstream DES tools have had many years start on Anylogic, and so the comparison may not be a fair one.

One conclusion from this is that there is undoubtedly an overhead to building hybrid models, both in development time for the conceptual model and also in the level of programming skill required. We are still some way away from the day when a novice user can develop a hybrid model, which runs, entirely by drag-and-drop in a graphical user interface, as they can today in a tool like Simul8. The question, which was the title of our 2013 WinterSim paper (Brailsford et al. 2013) is whether hybrid simulation is "the way forward, or more trouble than it's worth". Wouldn't it be lovely if we could use DES as a standalone paradigm and did not have to bother with building hybrid models?

4.3 Using DES for "ABM type problems"

In (Siebers et al., 2010) another of the SW10 panelists, Chick Macal, listed about a dozen reasons why ABM might be the preferred modeling paradigm over DES. In my response (Brailsford 2014) I selected (cherry-picked?) a few of these reasons, and described DES models which had been used for each case. Full details can be found in the original paper, but some are summarized in this section.

- ABM is preferred "*when agents have dynamic relationships with other agents"*. The HIV model presented in (Rauner et al. 2005) is a standard DES yet the mother and baby entities are linked, and the relationships (probabilities of HIV transmission) change over time as the baby grows and loses the immunity it was born with. Maintaining this dynamic link between mother and baby was vital for the accuracy of the model.
- ABM is preferred "*when the goal is modelling the behaviours of individuals in a diverse population*". Including patient behaviour in DES models was a key aim of the paper mentioned in Section 1.3 on screening for diabetic retinopathy (Brailsford and Schmidt, 2003). More recent work on screening for breast cancer (Brailsford et al., 2012) evaluates the effectiveness of different screening policies, where individual women's decisions to attend for screening are explicitly modeled in terms of psychological attributes. This model is more of a microsimulation than a true DES, as patients progress through the system one by one and do not compete for resources, but it is still definitely not an agent-based model.
- ABM is preferred "*when individual agents have spatial aspects to their behaviours*". We have already observed that pedestrian flow models are unusual amongst ABM models, in that they have been widely applied in commercial practice. ABM is regularly used in the design of public spaces such as sports stadia, train stations and shopping malls. The software used for this purpose is highly complex and hugely expensive, and in general such modeling work is undertaken by specialist consultancies using their own bespoke software. However, two Masters students at the University of Southampton used the DES tool Simul8 to model pedestrian flow in two different case studies, using standard features of Simul8 (work centers and queues) to count the numbers of people either in transit or at given locations, and identify zones of congestion risk.

5 A SPECIFIC EXAMPLE

In this section we shall discuss whether a specific ABS-DES hybrid model could have been written in DES alone. Viana et al. (2012) present a hybrid model for the sight condition age-related macular degeneration (AMD). This condition leads to loss of central vision and was until recently untreatable: now there is a treatment, but it requires regular monthly injections into the eye which need to be performed in a hospital setting. This has led to huge additional demand on hospital clinics, but obviously has meant a great improvement in quality of life and ability to remain independent for the older population.

The AMD model is being developed as part of the UK-based EPSRC-funded Care Life Cycle project (http://www.southampton.ac.uk/clc/), a multi-disciplinary project whose aim is to apply methods from complexity science to study the connections between supply and demand for health and social care in the context of an ageing population. AMD is a good exemplar condition since it perfectly illustrates the complex relationships between the UK health and social care systems. Patients with inadequate social support are less likely to attend appointments, mainly because of transport difficulties, and each missed appointment increases the risk of disease progression. Moreover, overcrowding in the clinic and inflexible transport arrangements can mean some patients who do manage to attend leave without being treated, since their transport turns up to take them home before they have been seen. A short-term cost for the National Health Service (running extra AMD clinics) leads to a long-term saving for the social care system (fewer people in the community requiring social support). The model is explained in detail in Viana et al. (2012). Brailsford et al. (2013) then discuss the choice of modeling paradigm(s) in this model and ask, was it worth the effort? Viana (2014a) goes on to compare this approach with the combined COTS approach he adopted for his model of chlamydia infection.

The model was developed in Anylogic v6. Admittedly part of the reason for using Anylogic, and for developing a hybrid model in the first place, was academic curiosity. However there was a better rationale than this for using a hybrid approach. To summarize briefly, there are two main components of the model: an ABM for the patient population, who are geographically distributed across the region surrounding the hospital and who are invited to attend the AMD clinic, and a DES model of the clinic itself. In addition, each patient agent contains a compartmental model representing the progression of AMD. On the face of it ABM seems a good choice for the community model. Geographical location is important, and each patient's probability of attending depends on a complex combination of factors which change dynamically over time. Moreover, although this is not yet included in the model, ABM allows the possibility of including "family and carer" agents and "medical staff" agents, with whom patient agents interact. For example, a daughter agent may need to take time off work to take her elderly mother to the hospital. Equally, DES seems a natural choice for the clinic model, which is really a straightforward queuing system. Whenever a scheduled appointment occurs for any agent, first the decision to attend is modeled and then the agent "moves across" and becomes an entity in the DES model.

However, to play devil's advocate again, there is no reason why the ABM part of the model could not have been modeled as a DES. All the characteristics of the agents, namely geographical location, distance from the hospital and normal means of transportation from home to hospital, stage of eye disease (in each eye) and level of social care support required and being received, could all be stored as conventional numerical properties of the entities. All these characteristics could be changed (indeed, would only change) during activities, so attributes like stage of eye disease which in reality change continuously, would only change at certain fixed points in time. The processes of disease progression and of changing need for social services support could be modeled like retinopathy in Brailsford and Schmidt (2003), which used Ruth Davies' Patient Oriented Simulation Technique software (Davies and Davies 1994) to allow entities to participate in multiple concurrent activities. Most modern DES COTS software now has similar facilities. While the entities were not directly participating in the clinic activities, they could be participating in an unconstrained activity "in the community" and then, when the time for a scheduled clinic appointment came, a similar decision rule to Brailsford and Schmidt (2003) could be invoked, which would use some mathematical function of the entity's characteristics to determine whether the patient attends their appointment, or returns to "in the community" for another month. In fact, this is pretty close to the way that the ABM works at the moment.

6 DISCUSSION

There is a fine line (and arguably a spurious or imaginary one) between ABM and DES. An ABM can be a DES: not all agent-based models proceed on a time-step basis. Not all agents live on a grid, or on any kind of topology. For both the hypothetical AMD standalone DES model, and in Brailsford and Schmidt (2003), it could be argued that ABM-like features were being embedded inside a DES in order to produce the mathematical equation which calculates the probability of attendance. Even in the Simul8 bar model in Section 3.3, ABM-like attributes are potentially assigned to the entities and their values used in some composite function to determine whether or not a person chooses to have another drink. Even this simple little model could perhaps be called a hybrid!

Moreover, such a function is still needed even for a standalone ABM: as we mentioned earlier, the programmer still has to specify (and code) the rules for the interactions of agents and environment, even though the rules may change over time and may be very complex. It would not be difficult to do this in a DES version of the AMD model: the rules would be exactly the same and would be invoked when required. Ad hoc "environmental" events could also occur: for example, at some point a character in a TV soap might develop AMD, which could stimulate public awareness and change all the probabilities of attendance. Such phenomena are frequently observed. This could be coded as a one-off event in the DES which changes the value of some global variables.

Although by now it may come as a surprise to the reader, I do not actually believe that ABM and DES are the same thing. There are certainly agent-based models which do not have a discrete-event engine or structure. I set myself the challenge of coding the car-race model in Simul8, and at the time of writing I have still not figured out how to do this in any remotely sensible way.

Clearly software maturity is highly relevant. As yet, most hybrid models mainly exist in the research domain and are not routinely used by practitioners. Anylogic is gradually changing this, as anyone who visits their website and looks at their list of clients can see, but it will not happen overnight. The decision to develop a hybrid model should not be taken lightly, especially in a consultancy setting where a client needs a quick answer. Additionally, design of experiments and interpretation of results becomes far more complicated in a hybrid model, where each submodel can be experimented with on a standalone basis and the total number of joint experiments with all submodels included increases exponentially with the number of models (Viana et al., 2014b).

So what is the take-home message from this paper? Suppose you are faced with modeling a problem which potentially has features which suggest both ABM and DES. If you are an experienced DES modeler and are familiar with a particular package, try DES alone first and only use a hybrid if you have to. Given the relative maturity of DES software, there is a very good chance that you will be able to model the required features within the DES environment, using the facilities of the software and with only a small amount of additional coding. Moreover, the full battery of analysis tools standard in such packages (optimization, automatic calculation of the number of iterations, variance reduction, output display tools and so on) will be at your disposal. However, if you are not a dyed-in-the-wool DES modeler, are open-minded, and have a working knowledge of Java, give Anylogic a go (there is a free one-month trial version).

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