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“Design for Survival Real-Time Infrastructures Coordination”

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DESIGN FOR SURVIVAL
REAL-TIME INFRASTRUCTURES COORDINATION

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Abstract
“First priority during disaster situations is, and should be, human survival”. This paper takes a systems engineering approach to the problem of operations coordination among multiple infrastructures in order to minimize the impact of large disasters on human lives and bring the system of infrastructures back to operation as soon as possible. Even though the human layer of disaster coordination is very important, the emphasis in this paper is on the physical layer. A solution framework in terms of multiple-delay difference equations is formulated to simulate the system of infrastructures in a step-by-step time domain solution suitable for real-time event-driven simulation. The form of the solution allows for dynamic system optimizations in scenario playing and during disaster operations. The present work is part of an effort by the Government of Canada, through the Natural Sciences and Engineering Research Council (NSERC) and Public Safety and Emergency Preparedness Canada (PSEPC) to fund research to develop innovative ways to mitigate large disaster situations. Our group at The University of British Columbia (UBC) is the largest of six University groups across Canada looking at various aspects of the problem.

Introduction
The recent Katrina disaster in New Orleans, which resulted in over 1,300 lives lost and 300,000 homes destroyed, is a dramatic example of the lack of quick coordinated response to mitigate the consequences of large disasters [1]. This failure in coordination occurred at a number of levels and perhaps in the case of Katrina the most important was at the decision making level. Regardless of the particular reasons for this failure, it can be assumed, nonetheless, that there was a general lack of appreciation of the full magnitude of the problem and of the dynamics of its development. These dynamics, driven by hard-to-predict specific events, would have required preparation scenarios and deployment responses commensurate with the magnitude of the events.

At present, most disaster simulation tools fall into two wide groups: a) At the high level of Emergency Preparedness Organizations, where a very wide macroscopic view of the problem is taken that may fail to account for unforeseen critical events, which in a highly nonlinear system, may actually trigger a sequence of catastrophic responses; and b) At the level of First
Responders, where a necessarily microscopic view of the problem needs to be taken but which may miss the larger picture.

In this paper we propose a systems engineering view of the problem. For example, in power systems, and in many other systems, the problem is one of transferring resources (tokens) from the location where the resources are produced (generators) to the location where the resources are utilized (loads). These locations are normally geographically separated. The system objective is to make sure that at any given moment in time, and under dynamically changing conditions of generation, load, and transportation system parameters, the tokens are distributed to the loads in an optimum manner. Transportation channels have limited channel capacity and time delays and these limitations will become particularly critical during emergencies. In addition, different infrastructures (the power grid, the water system, etc.) depend on each other at a number of points, but particularly at the level of the transportation systems, where they may influence each other’s channel capacity and delays. The proposed solution framework glues together the three physical components of the system: sources, loads, and transportation channels with the common lifeline of the flowing tokens.

The task of gluing together all the system components may appear quite daunting. However, this is an issue of granularity, and an important attribute of the solution framework proposed in this work is its adaptable “zoom” level. The same problem structure holds true at different levels of granularity. Depending on the zoom level one is at, the details outside the zoom box, or yet not visible inside the box, can be represented as combined equivalents. For example, in the case of the power grid, large bulks of power are delivered from hydro dams to large population centres over long distances at the transmission system level. At this level, entire population centres are represented as coarse single-load equivalents. Once the electricity arrives at the city’s substations, it is distributed to individual city zones at the distribution level. At the distribution level, it is now the transmission system that is represented as a coarse equivalent, while the various city zones are differentiated in more detail, though not yet to the level of individual city blocks. The process of zooming in can now be continued to the level of individual city blocks and finally to the level of individual buildings or houses.

**Problem Characterization**

**System of Infrastructures**

We can imagine the primitive man, as in the animal kingdom, to be self-sufficient. He had to provide for himself the food and shelter he needed for his basic survival. As civilization developed, tasks became specialized: one man could grow food for many while another could make clothes for many, and so and so on. The more complex our civilization has grown, the more specialized the tasks have become. In a twist of irony, however, as we continue to evolve, the more our specialized tasks have become intertwined with each other to the point that it is less and less possible to perform a given task independently of other tasks. Consider a simple three-sector model consisting of energy, food, and clothing [2]. A system matrix can be set up that relates the contributions from each of the sectors to the production of the other sectors. Consequently, the failure of any one of the sectors will have repercussions on all the others. In a complex, highly nonlinear system, when multiple infrastructures fail simultaneously, as in the case of large disasters, the equilibrium points can become quite sensitive and eventually unstable.

**Project’s Objective: The MITS Simulator**

Our project’s objective is to build a simulator of infrastructures, the “Multiple Infrastructures Tokens Simulator” (MITS), that can capture the complex dynamics that occur in a system of multiple infrastructures during large disaster situations.
In the course of normal life, when a problem happens in a given infrastructure, the operators of that infrastructure, for example the power grid, will have a well established set of procedures to follow in order to restore service within a reasonable amount of time. This is also true for the telecommunications network, the water distribution system, and in general for all individual infrastructures. During large disaster situations, however, more than one infrastructure will be damaged at the same time. Normal recovery procedures which, by and large, assume that the other interdependent infrastructures are available will now fail to meet the expected recovery times. Worse yet, the needed recovery times will be much shorter during emergencies than during normal life if large damage to people and property are to be avoided. During these situations, the recovery of the systems becomes highly interdependent, highly nonlinear, and possibly unstable. The recent large disaster situations across the world (e.g., tsunami in South Asia, and Katrina in the U.S.) illustrate the previous point and have shown that, by and large, the recovery responses have been highly inadequate.

The objective of our Multiple Infrastructures Tokens Simulator (MITS) is to model the network of networks that results when all infrastructures are brought into the picture simultaneously. The main challenge here is to avoid a level of granularity that only individual infrastructures know or need to know in order to perform their individual functions, while at the same time retaining the essential aspects that define the dynamics of the combined behaviour of all infrastructures put together. The simulation of the combined dynamics of the system of infrastructures is critical to achieve optimum stable solutions. These optimal solutions will allow for more effective global (national, regional, municipal) systems designs that minimize costs (capital costs as well as system recovery costs) while at the same time maximize their effectiveness to save lives during large disaster situations.

System Model

The description of a system of infrastructures requires at least two layers: the physical layer and the human layer. In this paper we will concentrate on the physical layer. Work is currently in progress in our group on the modelling of the human layer. In the final product, the two layers will be integrated.

Figures 1 and 2 illustrate two infrastructure networks, the medicines network and the electric power network. The medicines network was chosen as a discussion example because one is usually accustomed to thinking of electricity or water as a flow through electrical wires or water pipes but the concept is equally valid for any item that has to be transported from one node to another. The components of these networks are described next.

System Components

Before describing the proposed system model, we need to introduce some basic definitions [3], [4], [5]:

1. Tokens
2. Cells
3. Nodes
4. Transportation Channels

Tokens

Tokens are goods or services that are provided by some entity (e.g., manufacturer or distributor) to another entity that uses them. For example, a TV set is a token that a person (user) can get from a TV shop (provider, distributor). The TV shop, now as a user, can get the set from the TV factory (provider, creator). My dentist can provide me (user) with the token of his/her dental work (provider, creator).
Cells

A cell is an entity that performs a function. For example, a hospital is a cell that uses input tokens: electricity, water, medicines, etc. and produces output tokens: e.g., beds served. A city neighbourhood is a cell that uses tokens like electricity, water, food, shelter, and, depending on the system simulated, may produce “nothing” (like in the case of disaster victims).

Nodes

A node may group one or multiple cells. What defines a node is the separation in time or space between one node and another node. Two nodes are connected by transportation channels. A node is a generator of tokens if the tokens produced by its cells, or taken out from its storing facilities, are exported to other nodes. Similarly, a node can be a load if it receives tokens from other nodes which it then delivers to its internal cells for immediate use or storage. In the most general and common case a node will be a generator of some tokens and a load of other tokens.

Transportation Channels

Transportation channels are the means by which tokens flow from a generator node to a load node. A non-ideal channel (normal case) will constrain the number of tokens that can be transmitted from generator nodes to load nodes and will put a time delay before the tokens are received. If the channel is broken down, zero tokens can be transmitted through that channel.

Fig. 1 – Medicines Network (token 3)
There are two schools of thought in modelling economic systems where goods are produced and goods are consumed: “mathematical economics” and “literary economics” [6]. In mathematical economics, more akin to systems engineering, the logical relationships between entities and quantities are expressed in terms of mathematical symbols. In literary economics, the relationships are expressed in terms of predicate logic. Due to the large geo-temporal extension of the problem of coordinating infrastructures recovery dynamics during large disasters and due to the highly nonlinear nature of the relationships, we have chosen the mathematical equations approach to describe the physical layer of the system of infrastructures. This gives us access to the large pool of available mathematical tools and systems theory techniques for the solution of large and complex network systems. The analytical description also allows us to identify more readily the system’s weak points, instabilities, and directions where design changes can be made to achieve maximum system robustness at minimum costs.

In our Multiple Infrastructures Tokens Simulator (MITS), the components of the physical layer, tokens, cells, nodes, and transportation channels, are glued together by two levels of relationships. The first level is the cell equations where specific amounts of input tokens are needed to produce specific amounts of output tokens. Next, since the tokens are delivered through transportation networks from more than one generator node to more than one load node, the topological relationships and the channel characteristics (channel capacity and time delay) will give another set of conditions that must be satisfied.

**Delivery of Survival Tokens**

It is important to distinguish what the production objectives of the various sectors of our system of infrastructures are during normal life and during emergencies. Optimizations during normal life usually follow the model of minimizing cost per product or service produced. Time frames are only one of the factors. During emergencies, on the other hand, time delays
can make the difference between life and death. The function objective during emergencies
shifts from economical optimization to saving human lives.

To maximize saved human lives during large disasters, we need first to identify the basic
survival tokens that are needed by the victims of the disaster and then optimize the system to
deliver these tokens within the time constraints of human survival.

Survival Tokens
Even though lists of survival tokens can be found in a number of sources, we would still like
to summarize our own list here. We subdivide the survival needs into two groups: a) related to
the individual’s needs, and b) related to the group’s needs.

Individual Needs:
- Potable Water (suitable for drinking)
- Food (adequate for emergency situations)
- Body Shelter (breathable air, clothing, temperature, housing)
- Personal Communication (whereabouts of loved ones)
- Individual Preparedness (education)
- Sanitation (waste disposal, washing)
- Medical Care (medicines, physicians, nurses)

Group Needs
- Panic Control (hope, political and religious leaders, psychologists, media)
- Civil Order (fire fighters, police, army)

Our system optimization objective is to deliver these vital survival tokens on the time scale
ddictated by human survival needs. A companion paper “Dynamic Islanding of Critical
Infrastructures, A Suitable Strategy to Survive and Mitigate Critical Events” [7] discusses a
cooperation framework of public and private sector policies to implement a coordinated
strategy to meet the survival timelines. The present paper deals with the physical constraints
for the delivery of survival tokens on the physical layer. As indicated, another subgroup in our
team is working on the modelling of the human layer of decision making for the delivery of
these tokens. Yet another of our subgroups is working on the aspects related to Group Needs.

Infrastructure Networks
As described, the physical layer of a particular infrastructure can be considered as made up of
tokens, cells, nodes, and transportation channels. Tokens are produced at generating cells and
delivered from the nodes where these cells are located. Tokens are consumed by load cells
that are located at receiving nodes. Tokens are transported from one node to another by the
transportation channels. In general, each token has its own transportation channel, for
example, electric wires for electricity and pipes for water. Some channels, however, may be
shared by many tokens, for example, medicines and food can be transported together by
trucks travelling on roads, or by planes using airports, etc.

To facilitate the presentation, it will be assumed in what follows that we have only one cell
per node and we will not attempt to make a distinction in terms of subscripts.

Cell Equations
Figure 3 below illustrates a hospital cell. The cell’s job can be characterized using an input-
output model [2]. The cell uses a number of input tokens: electricity, water, medicines,
doctors, and nurses to produce an output token: hospital beds. A given token in the cell will
then be denoted as \( x_{kj} \). The first subscript will indicate the node number in the network of Fig. 1. The hospital is node \( k = 2 \). The second subscript will indicate the type of token, for example medicines is token \( j = 3 \). The tokens in the hospital cell (Fig. 3) are

(1) \( x_{21} = \) electricity, \( x_{22} = \) water, \( x_{23} = \) medicines, \( x_{24} = \) doctors, \( x_{25} = \) nurses, \( x_{26} = \) beds

If we assume for simplicity that the relationship between input and output is a linear one \((\text{which in the case of the hospital is not})\), we can say that to produce a number of beds (output) we need a certain amount of each of the input tokens and, for generality, of the output itself (e.g., worn out beds or old equipment). Mathematically,

(2) \( x_{26}(t) = a_1 x_{21}(t) + a_2 x_{22}(t) + a_3 x_{23}(t) + a_4 x_{24}(t) + a_5 x_{25}(t) + a_6 x_{26}(t) \)

The coefficients \( a_j \) indicate how many units of token \( j \) are needed per unit of output token 6 (hospital beds). It is easy to see that in this example the relationship cannot be linear. Indeed, if only electricity (token 1) was available, but there were no doctors, no medicines, etc., the output (beds) would have to be zero. The correct relationship among tokens in (2) needs to be expressed by some nonlinear function,

(3) \( x_{26}(t) = f_2(x_{21}(t), x_{22}(t), x_{23}(t), x_{24}(t), x_{25}(t), x_{26}(t)) \)

\( x_{kj} = \) token \( j \) used or produced in cell \( k \)

\( x_{21} = \) electricity used
\( x_{22} = \) water used
\( x_{23} = \) medicines used
\( x_{24} = \) doctors used
\( x_{25} = \) nurses used
\( x_{26} = \) beds produced
\( x_{26} = f\{x_{21}, x_{22}, x_{23}, x_{24}, x_{25}, x_{26}\} \)

Fig. 3 – Hospital Cell

To generalize, if for the hospital (node 2), we define a vector of tokens

(4) \( \overline{X}_2(t) = \begin{bmatrix} x_{21}(t) \\ x_{22}(t) \\ x_{23}(t) \\ x_{24}(t) \\ x_{25}(t) \\ x_{26}(t) \end{bmatrix} \)

Then the hospital cell must satisfy the vector function

(5) \( f_2(\overline{X}_2) = 0 \)
All cells in the medicines network of Fig. 1 must satisfy their internal cell functions, i.e.

\[
\begin{align*}
  f_1(X_1) &= 0 \\
  f_2(X_2) &= 0 \\
  f_3(X_3) &= 0 \\
  f_4(X_4) &= 0
\end{align*}
\]

Similarly, all cells in the electric power network of Fig. 2 must satisfy their own internal functions of the form in (6) and the same applies to the water network, etc.

Notice that the medicines network of Fig. 1 only carries the medicines token. The other tokens in the hospital cell vector of (4) are transported by other networks (electricity is transported by the electric power network, etc.). Cell level is one level where multiple infrastructures come together. The other level, to be discussed subsequently, is the transmission system level.

The hospital as a cell is connected to all the networks that provide the tokens it needs to manufacture its product (beds) and is also connected to the recipients of its product (patients). The diagram in Fig. 4 illustrates these relationships. Each arrow in this diagram corresponds to an entire token network, such as the medicines network of Fig. 1 and the electric power network of Fig. 2.

![Fig.4 – Tokens Flow Diagram for the Hospital Cell](image)

**Network Equations**

The tokens needed at the nodes for the cells to do their jobs will in general (apart from local storage) have to come from the other nodes. For a token that has to be delivered to the cell, the cell will be a load node. The tokens will travel through the transportation network from generator nodes to load nodes. For a given token, multiple generator nodes of that token may exist and likewise multiple load nodes for that token may exist. There will be multiple channels linking generator nodes to load nodes. For a given generator node, dispatching decisions will determine how the node’s token production will be distributed among the channels coming out of the node. Once the tokens are in the channels, they will be affected by the channel’s capacity and transportation delays. After the transportation delay, the tokens will arrive at the load node connected to that channel. For that load node, the tokens received at a given time instant will be the sum of the tokens arriving from all channels connected to it. How many token units are received at a given load node at a given time instant will depend on the total amount of tokens generated in the system, on the dispatching decisions, and on the channels capacity and delays.
Transportation Channels

Consider again the example of the hospital cell. Suppose that because of an emergency, the number of patients per hour it needs to treat has exhausted the medicines in the storage room. Additional medicines need to be delivered by the medicines network of Fig. 1. Using a telecommunications link, requests \( R \) are made to Medicine Suppliers A and B located in Nodes 4 and 1. After an analysis of the situation (using, for example, centralized analysis with our MITS simulator), it is decided that Supplier A at Node 4 will dispatch to the Hospital at Node 2 the amount of \( D_{42} \) medicines and Supplier B at Node 1 will dispatch \( D_{12} \) medicines. Supplier A will put the medicines in a delivery truck (assume the supplier owns the truck). This truck is to travel through the city from the location of Node 4 to the location of Node 2. In making this delivery, the medicines network will be using facilities from the “roads network”. However, for the purpose of the medicines delivery, the particular streets used is not relevant, what is important is how long it will take for the truck to make its trip from Node 4 to Node 2 (“channel delay”). It is up to the roads network to advise the medicines network (infrastructure interdependency) as to which combination of streets will result in the shortest delivery time. The roads network will provide the medicines network with the “channel characteristics” for the medicines to be transported from Node 4 to Node 2 and for Node 1 to Node 2. Only the roads network can provide the information of the channel delays to the medicines network because other vehicles, from other networks, will be simultaneously using the road network’s facilities.

Channel Model

The medicines that Node 4 will dispatch to Node 2 will travel through the 42 channel. We can postulate the following relationship between the tokens received at 2 and the tokens sent at 4 (Fig. 5):

\[
x_{4\rightarrow 2}(t) = g_{4\rightarrow 2}D_{4\rightarrow 2}(t) = m_{4\rightarrow 2}z^{-k_{4\rightarrow 2}}D_{4\rightarrow 2}(t)
\]

where subscript \( \lambda \) stands for “link”.

Parameter \( g_{4\rightarrow 2} \) is the “conductance” of the channel and has two parts: \( m_{4\rightarrow 2} \) for magnitude and \( z^{-k_{4\rightarrow 2}} \) for time delay. Mathematically \( z^{-k} \) is the “time delay operator” \[8\] defined as \( z^{-k} f(t) = f(t - k) \). If there are no medicines lost or damaged during the trip, \( m = 1 \), and if the trip takes two hours, \( k_{4\rightarrow 2} = 2 \) (assuming one time delay unit is one hour). Equation (7) then becomes

\[
x_{4\rightarrow 2}(t) = D_{4\rightarrow 2}(t - 2)
\]

Equation (8) says that the medicines arriving at Node 2 at a given time are the same as the medicines dispatched from Node 4 two hours earlier.
The symbol for the channel model in Fig. 5 is borrowed from wave propagation in electrical transmission lines (a wave injected at the sending end of an electrical transmission line will arrive at the receiving end after the line travelling time).

In transportation systems such as roads, the channel delay will be a function of the distance between sending node and receiving node and of the amount of traffic from all the networks using those roads (congestion). The larger the distance and the more the congestion, the longer the time delay will be. In other transportation systems, such as electric power, there is no transportation delay within the time frame of human events since electricity travels at the speed of light. However, there is a maximum amount of power that can be carried by a given power “corridor” (consisting, for example, of overhead lines, transformers, and other equipment). In the MITS simulator, the power corridors in the electrical network (Fig. 2) would use the model of Fig. 5 with zero travelling time \( k_{12} = 0 \). Power losses in the conductors can be accounted (if so desired) by a value of \( m_{12} < 1 \) The maximum channel capacity should be considered as a limit in the dispatch block \( D_{12} \). In the water system there might be both a channel capacity and a transportation delay.

Broken links or reduced capacity links during disaster situations can be modelled easily with the model of Fig. 5. If the medicines truck route involves a broken road that is expected to be repaired in three hours, the link delay in Fig. 5 would be five hours (three hours for the road repair and two hours for the truck’s travelling time). If an electric power line has to be disconnected for four hours due to a fault, the link model for the line would include the transmission line maximum power capacity plus a delay of four hours.

**Continuity Equations**

Consider a load node and a generator node in a token transportation network (Fig. 6). The continuity equation requires that the sum of all tokens arriving at a load node from all links connected to the node must equal the total of the tokens going into the node’s cells. Similarly for a generator node the sum of all dispatches must equal the total tokens generated. These equations correspond to Kirchhoff’s current law (KCL) in electrical circuits.

![Fig. 6 Continuity Equation at Nodes](image)

Mathematically, for the examples in Fig. 6,

\[
(9) \quad x_2(t) = \sum_{i=1}^{p_3} x_{i2}(t)
\]

\[
(10) \quad x_4(t) = \sum_{i=1}^{p_1} D_{i4}(t)
\]
Dispatching Decisions

It is the dispatching decision at a generator node that determines how much of the token amount generated at the node, e.g., $x_3(t)$ in Fig. 6, will be travelling out of the individual channels connected to the node, i.e., $D_{42}(t), D_{43}(t), D_{45}(t)$. The only network condition that needs to be satisfied is the continuity condition of (10). After the dispatching decision has been made, the capacity and delay of the channel will determine the token amounts received at the different load nodes.

Efficient System Solution and System Optimization

The network conditions of (9) and (10), together with the channel equations of (7), allow us to set up a system of difference equations that contain the spatial-temporal constraints on a given token’s availability to perform a given cell’s function (6). The network conditions apply to each token separately: there is a network for each token. The cell functions integrate all the tokens. It is also important to note that the network equations for each token constitute a system of linear equations at each instant $t$ of the system solution, while the cell equations are nonlinear. This is a very important characteristic of the approach suggested in this paper. By separating the linear parts from the nonlinear parts of the solution, the iterations needed to satisfy the nonlinear parts are much faster and simpler, and considerable gains in solution speeds can be achieved. This is the same solution strategy followed in the real time power system simulator of [9] where speed gains of several orders of magnitude are achieved [10].

The equations for the system of infrastructures form a system of discrete time equations with high-order delays contributed by the transportation equations. These time delays define the dynamics of the system. The system of discrete time equations is solved one time step at the time, i.e., at $t = 0, \Delta t, 2\Delta t, 3\Delta t, \Lambda$ using the well-developed techniques of [12] and [9]. Linearizing the cell nonlinearities at each time step, one can set up the solution in terms of network matrices and obtain important system dynamics. Among the possibilities: a) Eigenvalues for system stability and delimitation of critical zones; b) Jacobian matrices for gradients and direction towards optimization; and c) Hessian matrices for maxima and minima operating regions. These tools allow for optimum designs within given system constraints.

An essential objective during disaster simulations is to make sure that the system resources are made available to the victims in the required amounts and within the needed timelines. For a given amount of system resources, the amount of tokens delivered to a given node will depend on the dispatching decisions. The proposed solution framework in terms of network tokens flow allows the formulation of this problem as an optimum dispatch problem, for which abundant literature exists, for example, in the field of electric power transmission [11].

Another advantage of the proposed network solution is its ability to integrate with other solution layers. For example, many of the functions of the human decisions layer can be integrated with the channels dispatching blocks ($D_{ik}$) and many of the functions of system monitoring and assessment can be integrated with the channel’s capacity and delay times (e.g., channel down times and repair times estimation).

Conclusions, Future Work, and Acknowledgements

This paper has presented some of the work of the JIIRP team at the University of British Columbia, which is part of the Joint Infrastructures Interdependencies Research Program (JIIRP) sponsored by the Government of Canada. Our group includes fourteen researchers from a number of disciplines in engineering, computer science, commerce, and psychology. It is the JIIRP’s program’s mandate to develop innovative solutions that can assist in the urgent
task of mitigating the loss of human lives and property that result from large disaster situations. The methodology introduced in this paper aims at providing a systems solution framework to the combined workings of multiple infrastructure systems. The paper addresses the problem of finding mathematical solutions for the physical layer. Equally, or in some cases even more important, are the solutions at the human decision making layer. This aspect is being addressed by one of the groups in our team. The expectation is to be able to integrate the methodologies developed for the human layer with those developed for the physical layer. A very important aspect of the integration of the human layer with the physical layer is system visualization and online asset management. We have another group in the team concentrating on these aspects. We are working with GIS systems and databases to coordinate actions across multiple infrastructures and across multiple layers of management responsibilities. Finally, another group in our team is looking at the aspects of human behaviour (panic control) during disasters, while yet another group is looking at the role of education of the public and of the information media for a better understanding of the events and expectations during large disaster situations.

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