PRES ‘15

P-Graph Approach to Allocation of Inoperability in Urban Infrastructure Systems

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Presentation Outline

- Introduction
- Problem Statement
- IIM Methodology
- P-Graph Methodology
- Case study
- Conclusions
- Future Work

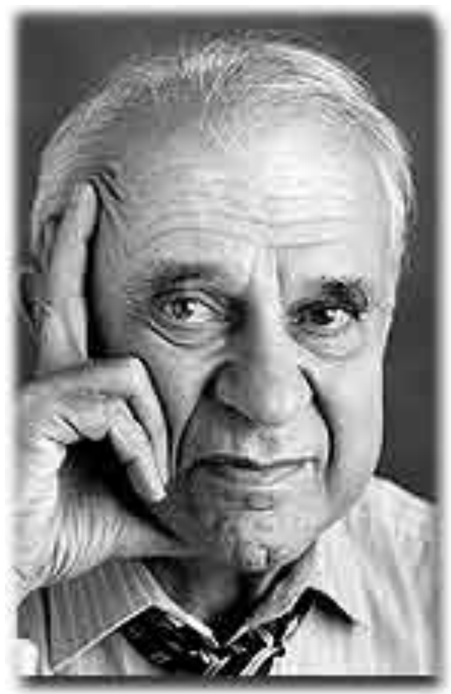
Introduction

- Risk analysis has developed as an essential means of ensuring the safe operations of increasingly complex man-made systems.
- It is now recognized that systematic approaches are needed to understand both potential causes and consequences of adverse events.
- Kaplan and Garrick (1981)
  - What can go wrong?
  - What is the likelihood of each adverse event?
  - What are the consequences of each adverse event?
- In this paper, a P-graph based approach is proposed for the allocation of inoperability to interdependent urban infrastructure systems under an IIM framework. This hybrid methodology allows ripple effects caused to be managed to ensure that minimal overall damage is incurred for the system.

Problem Statement

- Given a system comprised of multiple infrastructure system components with known levels of mutual interdependency
- Given an adverse event that induces an initial inoperability in a subset of the said system components
- Given a function that describes the total system-level dysfunction (i.e., aggregated inoperability), taking into account both direct and indirect impacts of the adverse event
- The problem is to allocate reduced infrastructure capacity to give the minimum level of total system-level dysfunction

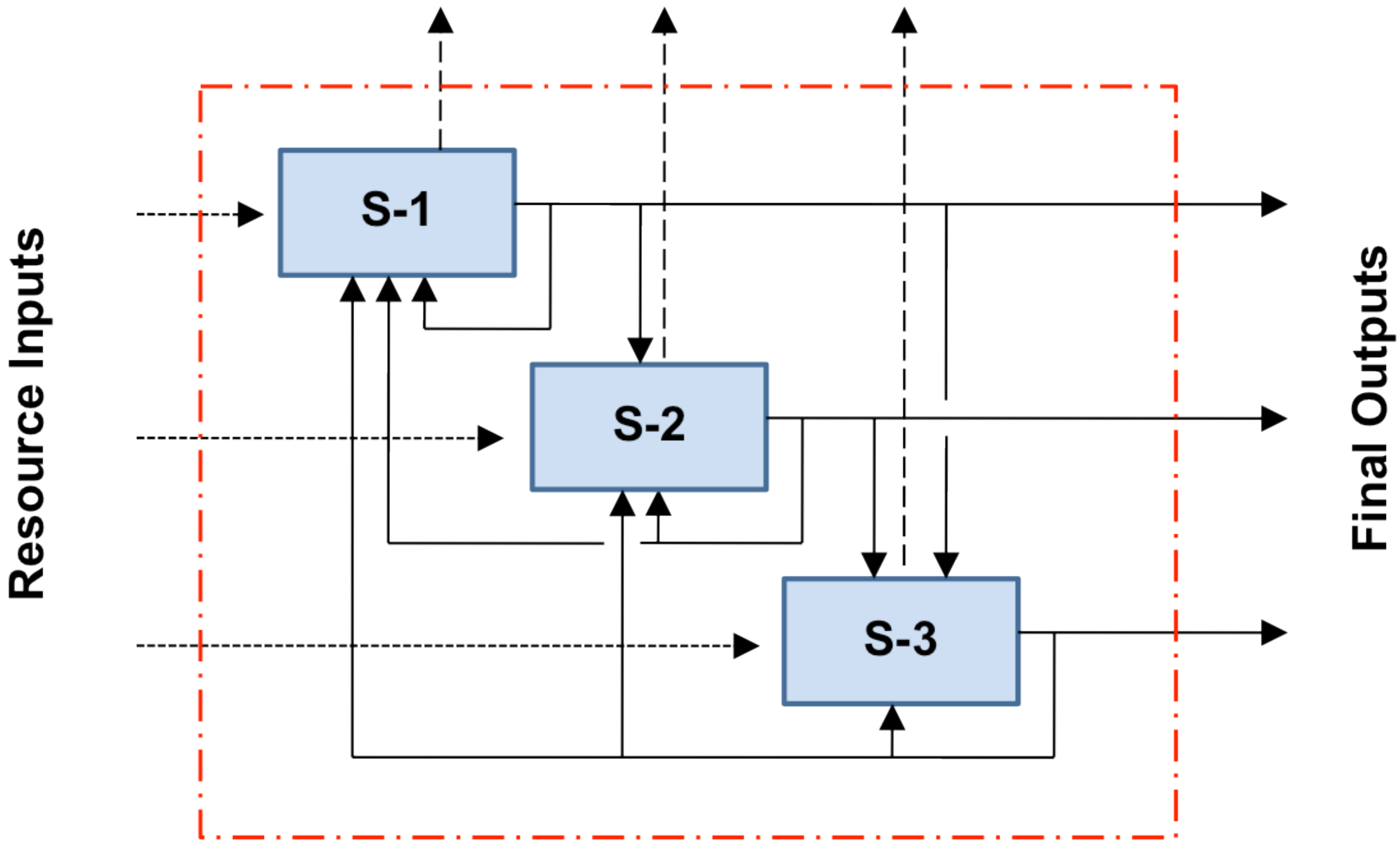
Input-Output Analysis: Historical Perspective



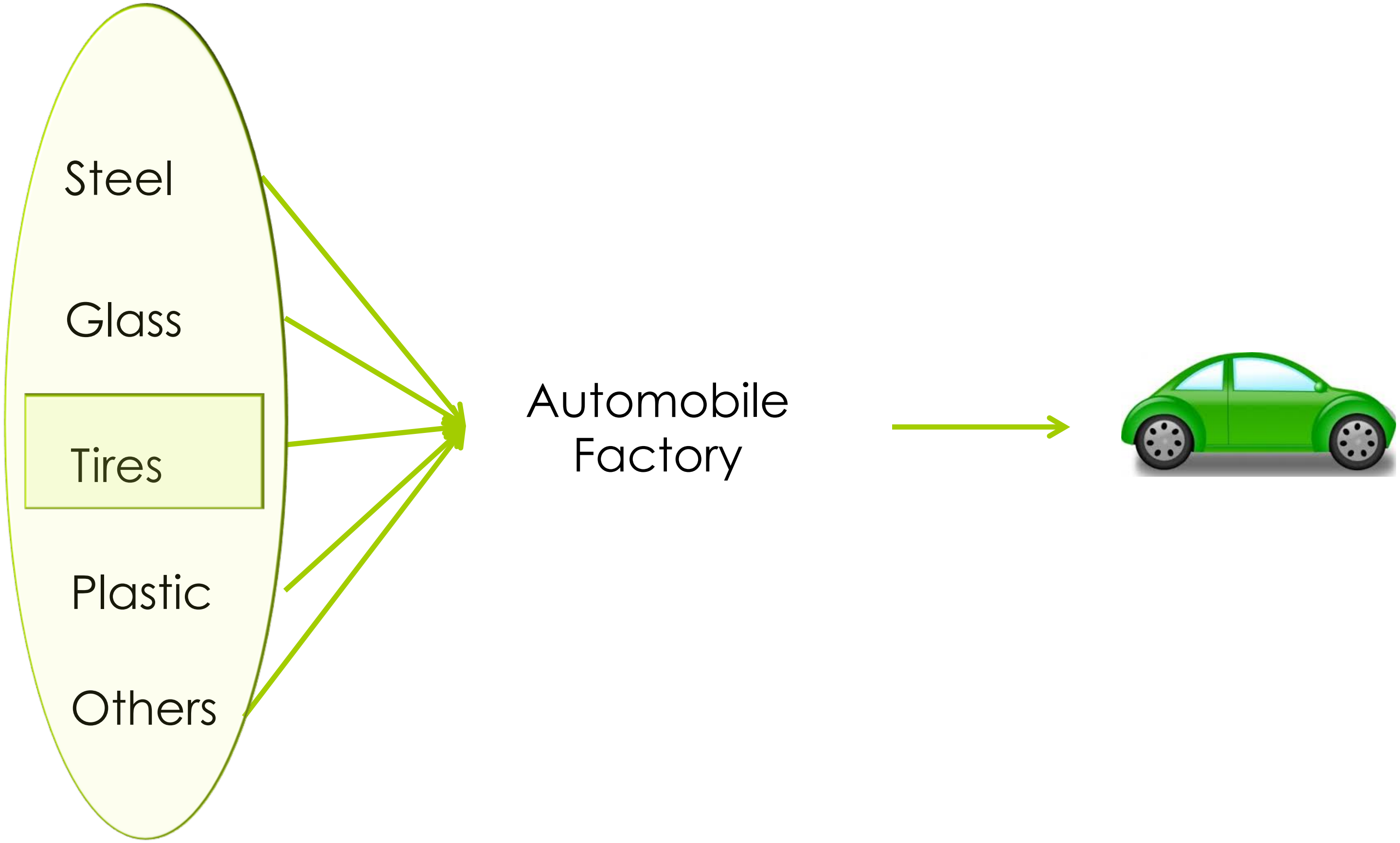
Wassily Leontief received the *Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 1973*

"for the development of the input-output method and for its application to important economic problems"

A Three-Sector Input-Output System



Basic I-O Logic



Basic I-O Logic

From a tire producer's perspective

Final Demand
End-users

Tires

Automobile Factory

Truck Manufacturer

Bus Operator

Intermediate Demand

Input-Output Analysis

- Illustrates macroeconomic activity as a system of interrelated goods and services
- various economic sectors as a series of inputs of source materials (or services) and outputs of finished or semi-finished goods (or services)
- Shows the inter-industry flow of goods and services in a given time period.

Input-Output Modeling

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y}$$

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$$

Where:

x	= total output vector
y	= final demand vector
A	= technical coefficient matrix
$\mathbf{(I\text{-}A)^{-1}}$	= Leontief Inverse matrix

Inoperability Input Output Modeling

$$c_i^* = \frac{\tilde{y}_i - \overline{y}_i}{\tilde{x}_i}$$

$$\mathbf{q} = (\mathbf{I} - \mathbf{A}^*)^{-1}\mathbf{c}^*$$

Where:

- c_i^* = normalized perturbation for sector i
- $\tilde{y}_i$ = ideal demand for sector i
- $\overline{y}_i$ = degraded demand for sector i
- $\overline{x}_i$ = ideal output for sector i
- $\mathbf{q}$ = inoperability vector
- $\mathbf{A}^*$ = interdependency matrix

IIM as an LP model

minimize $\mathbf{w}^{T}\mathbf{q}$
subject to:

$$(\mathbf{I} - \mathbf{A}^*)\ \mathbf{q} = \mathbf{c}^*$$

$$\mathbf{c}^*_L \leq \mathbf{c}^* \leq \mathbf{c}^*_U$$

$$0 \leq q_j \leq 1 \qquad \forall j$$

Where:

$\mathbf{w}$ = weight vector
$\mathbf{c}^*_L$ = final demand vector
$\mathbf{c}^*_U$ = technical coefficient matrix

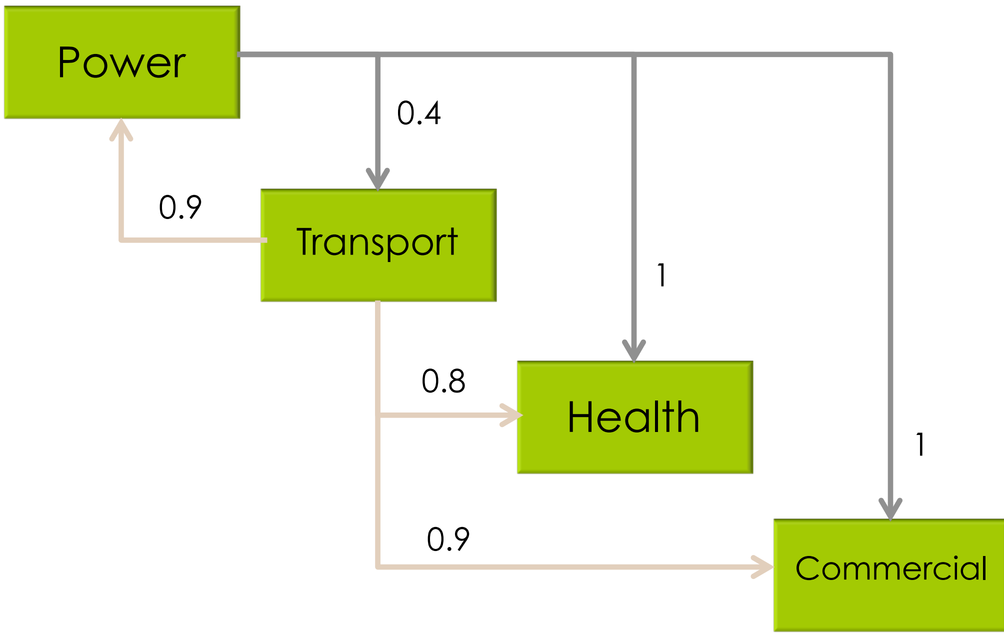
P-graph

- a graph theoretic approach to solving process network synthesis (PNS) problems
- the rigorous approach to maximal structure generation is an important element to ensuring a comprehensive coverage of possible solutions (Friedler et al., 1993)
- P-graph methodology is based on the description of streams and process units.
  - **Maximal structure generation (MSG)** – the identification of all possible connections given a predefined set of processes.
  - **Solution structure generation (SSG)** – the identification of feasible subsets of the maximal structure, each of which represents a candidate solution topology
  - **Accelerated branch and bound (ABB)** – the identification of an optimal solution, where reduction of computing effort is achieved by restricting search to the feasible solution structures only

Case Study

- Four-component urban infrastructure system
  - Component 1 – Power infrastructure (e.g., power plant and transmission grid)
  - Component 2 – Transportation infrastructure (e.g., road and rail networks)
  - Component 3 – Health infrastructure (e.g., hospitals and clinics)
  - Component 4 – Commercial infrastructure (e.g., grocery stores and retail outlets)

Case Study



Leontief-Based Model of Risk in Complex Interconnected Infrastructures

By Yacov Y. Haimes[1] and Pu Jiang[2]

Abstract: Wassily Leontief received the 1973 Nobel Price in Economics for developing what came to be known as the Leontief input-output model of the economy. Leontief's model enables understanding the interconnectedness among the various sectors of an economy and forecasting the effect on one segment of a change in another. A Leontief-based infrastructure input-output model is developed here to enable an accounting of the intraconnectedness within each critical infrastructure as well as the interconnectedness among them. The linear input/output model is then generalized into a generic risk model with the former as the first-order approximation. A preliminary study of the dynamics of risk of inoperability is discussed, using a Leontief-based dynamic model. Several examples are presented to illustrate the theory and its applications.

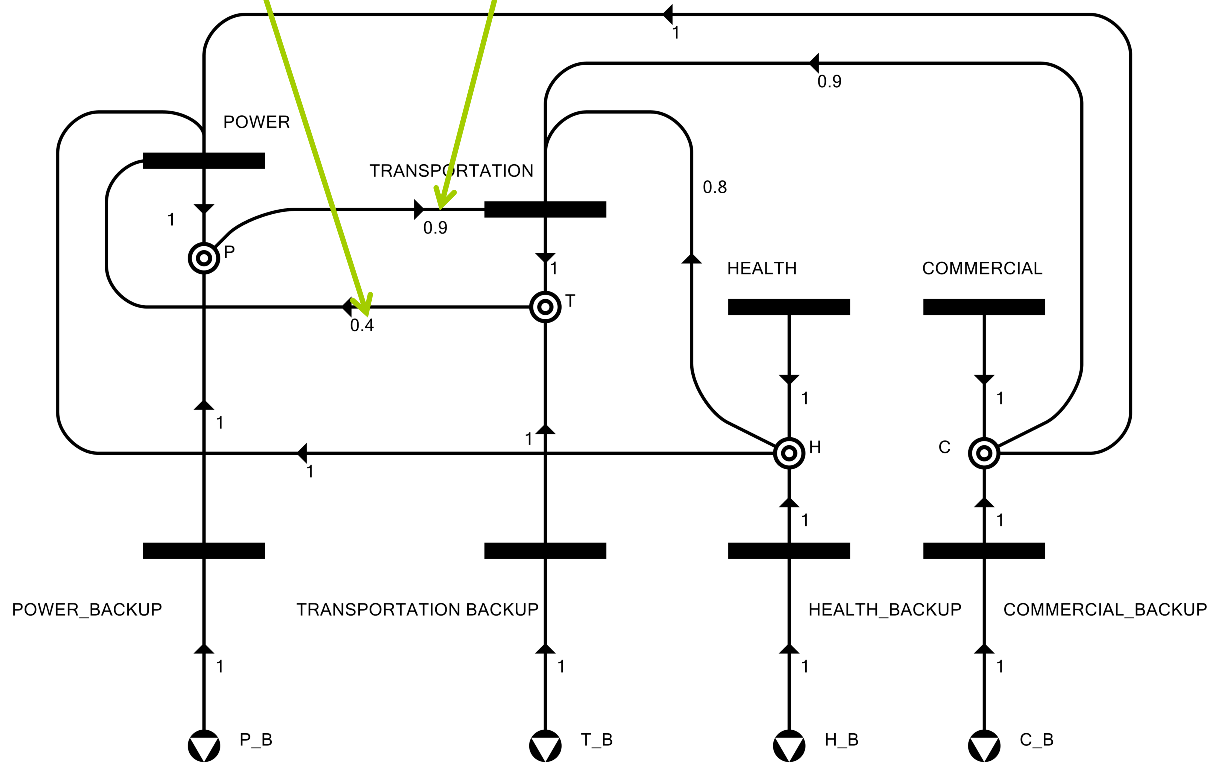
CKGROUND

The advancement in information technology has markedly increased the interconnectedness and interdependencies of our critical infrastructures, such as telecommunications, electrical power systems, gas and oil storage and transportation, banking and finance, transportation, water-supply systems, emergency services, and continuity of government. There is an urgent emerging need to better understand and advance the art and science of modeling complexity and of interconnected large-scale complex systems; this need stems from the increasing

for generations (Haimes 1999). We know, for example, that the quality and quantity of ground water of unconfined aquifer systems interact with and are functions of the quality and quantity of surface water. Furthermore, the quality and quantity of surface and ground water are functions of the quality of point and nonpoint discharges of treated or untreated effluents. In addition, the quality of surface and ground water is closely dependent on the land-use and management practices of the watershed. Natural phenomena such as floods, droughts, hurricanes, climate change, and major earthquakes have their own critical influences on the quality and quantity of surface

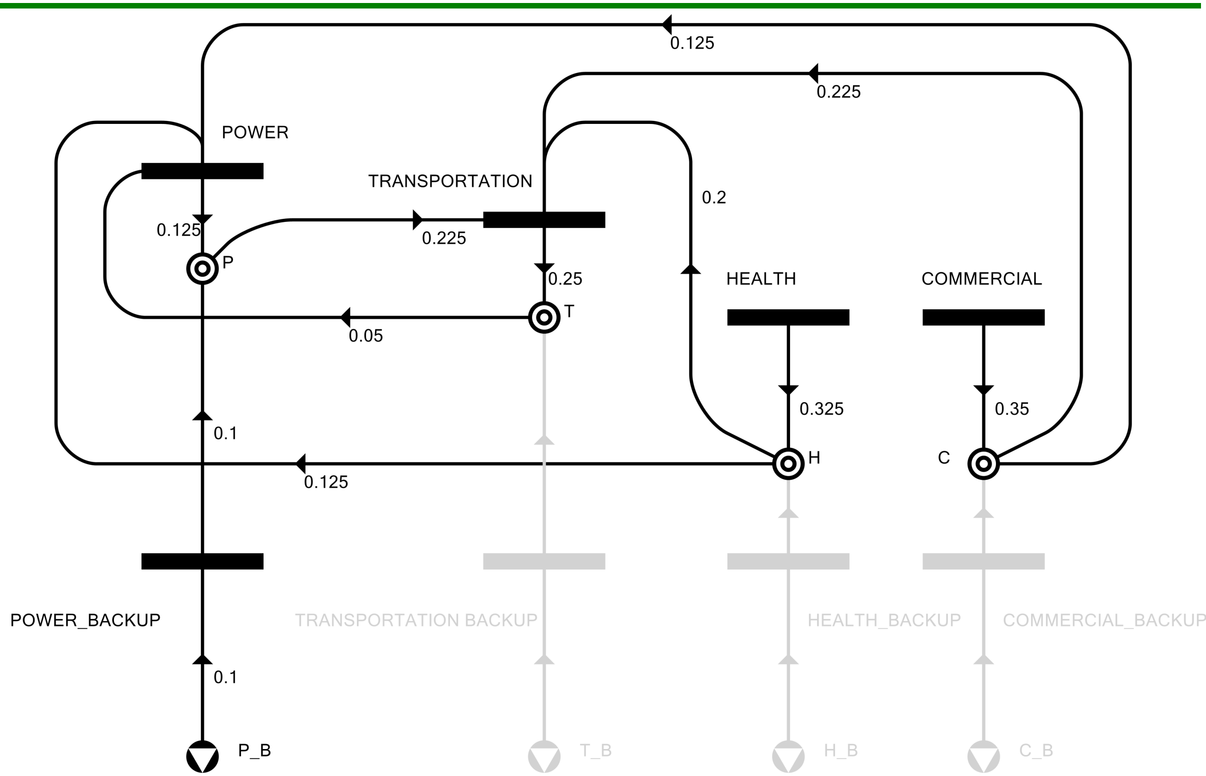
Case Study

	j = 1	*j* = 2	*j* = 3	*j* = 4
i = 1	0	0.9	0	0
i = 2	0.4	0	0	0
i = 3	1	0.8	0	0
i = 4	1	0.9	0	0



Case Study

	Perturbation	Inoperability
Power infrastructure	–0.1	0.125
Transportation infrastructure	+0.2	0.250
Health infrastructure	0	0.325
Commercial infrastructure	0	0.350



Conclusions

- This hybrid methodology enables limited system capacity to be allocated in order to minimize system-wide losses incurred as ripple effects cascade through interdependent system components

- A case study from literature involving interdependent urban infrastructure systems was solved to illustrate this approach.

- The solution achieved via P-graph methodology in this example identifies how excess capacity in electricity generation can be activated during the crisis to mitigate inoperability in other key system components.

Future Work

- Similar principles can be readily extended to more complex urban infrastructure systems.

- address research issues pertaining to calibration of the interdependency matrix and definition of priority weights assigned to each infrastructure system

- This approach may further be extended for optimal planning of spare capacity.

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Thank you.

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