Intelligent systems: issues and trends

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Intelligent Systems: Issues and Trends

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Abstract

The paper reviews issues and trends in the field of embedded Intelligent Systems considering questions such as: What is intelligence? Why do we need intelligent machines and systems? What design methods are available for designing these systems? A framework for designing intelligent systems developed by the author is outlined. Three types of external behaviour of machines are contrasted: programmed behaviour (automation), proto-intelligent behaviour (self-regulation) and intelligent behaviour (the capability for coping with poorly structured and changing working environment, learning from operators, learning from own experience, self-maintenance, self-repair and resolving conflicting demands by negotiation with other parties). The paper considers the concept of Intelligent System Architecture and discusses the selection of an appropriate architecture with a view to obtaining desired external behaviour. In particular, the discussion centres on architectures which facilitate reliability, self-diagnosing, self-reconfiguring, safety and incremental development. Trends towards multi-agent systems are reviewed and assessed in some detail.

Keywords: intelligent systems, autonomous agents, artificial intelligence in engineering, intelligent manufacturing

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1. INTRODUCTION

Current volatile demand and supply conditions, social pressures for a better working environment and the new consumer ethics favouring green processes and products have provoked considerable interest in industry for flexible (responsive) and autonomous machines. The demand is for machines capable of working in hostile conditions without supervision; for manufacturing tools able to cope, without human intervention, with sudden changes in production schedules and product ranges; for reliable, fail-safe machines; for devices seeking to reduce harmful effects on ecology under variable operational conditions; for machines, vehicles and systems capable of interacting and evolving with the changing world in which they operate. Conventional schedulers and controllers make machines too rigid to meet this demand.

Attempts to build artificial intelligence into machines and thus provide them with a degree of autonomy and responsiveness are pursued vigorously in research laboratories around the world. My own ideas how to achieve this goal evolved with the accumulation of experience and I take this opportunity to review my current thinking and formulate a tentative intellectual framework for designing future generations of intelligent systems. The proposed framework is a further development of my ideas published in [1, 2, 3, 4, 5].

2. FUNDAMENTAL CONCEPTS

2.1 Machines and Systems

For the purposes of my research I use the term *machine* to depict any man-made object that interacts with its environment by exchanging information, energy and/or matter. A real machine must have a mechanical structure which supports and houses components that handle the three flows, as illustrated in Table 1. An abstract machine consists of statements and has no physical components.

A machine imports from the environment the required energy, usually in chemical or electrical form, converts it into mechanical energy and disposes of the surplus as heat, sound, mechanical vibrations or chemical substances. The energy conversion is usually done by means of an internal combustion engine (cars, aircraft), by solar cells (satellites) or batteries (cameras), unless the required energy is supplied continuously from a suitable electricity supply system (machine-tools, high-speed machines, appliances). Mechanical interaction with the environment is accomplished by means of *effectors*, such as: grippers, arms, wheels, shutters, wings, jets and keyboards.

One important class of machines has considerable capacity for collecting, storing, processing and distributing information. Such machines receive information from their environment through sensors eg, thermometers, pressure pads, laser bar-code readers, photo-sensitive cells, video cameras, radar and sonar, and send information to the environment by means of signalling, broadcasting, printing or display equipment eg, flashing lights, sirens, printers, display panels and screens. The acquired information is, as a rule, digitised, stored in digital memories, processed by digital processors and transmitted through digital communication networks.

	INFORMATION	**ENERGY**	**MATTER**

COLLECTION	laser ranger video camera	charger	from cooling liquid reservoir
STORAGE	ROM RAM	batteries	plastic vessel
PROCESSING (CONVERSION)	data fusion	stepping motor	purifying filters
DISTRIBUTION (TRANSPORT)	AppleTalk network	mechanical shafts, differential	plastic conduits
USE	trigger for motors	wheels	cooling of cutters
SENDING (DISPOSING)	monthly report	vibrations heat	closed circuit fluid flow

Table 1. Flows of information, energy and matter in a machine

In addition, most practical machines handle flows of matter, usually fluids but occasionally also solids. Examples include liquid or solid fuel, cooling fluids, swarf, packaging material, pallets with parts and similar.

I use the word *system* to describe any set of elements interconnected with a purpose, including a set of interconnected machine components (a machine) or a set of interconnected machines (a machine system).

2.2 Planning and Controlling Behaviour of Machines

The operation and maintenance of machines has to be planned and their behaviour controlled. In other words, machines have to be *managed* (the term machine *management* is used here as a synonym for planning and control).

The simplest machines are managed by their operators ie, their users. More advanced machines are either constructed like clockwork or *programmed* to behave in a particular manner. The pattern of behaviour of such machines is fixed whatever the external conditions and will change only if their structure or control programs are changed. There are, however, machines with built-in self-management systems that are capable of modifying their own behaviour, at least to a certain degree, whenever there is a need to accommodate an unexpected change. These machines will be referred to throughout this paper as *intelligent*. The simpler variety of such machines, those capable of coping with well defined changes only, will be named *proto-intelligent*.

2.3 Intelligence

The two concepts that are fundamental to the design of intelligent machines are *information* and *intelligence*. For the purposes of my research I define them as follows.

> *Information is a means of reducing uncertainty about an aspect of the Universe.* It is a natural resource, like energy and matter. Information is used for reducing risks associated with decision making, for accumulating knowledge and for organising (structuring) the world.

> *Intelligence is the capability of a system to achieve a goal or sustain desired behaviour under conditions of uncertainty.* It is a property which enables the system to operate effectively in the absence of relevant information. The ability to recognise partially specified patterns is the key to intelligent behaviour.

The implications for the design of machines are very important. If it is not feasible to create for machines a deterministic operational world, machines should be designed to have appropriate sensors and associated information processing facilities to enable them to reduce uncertainty about their environment and their own state of operational readiness. If machines themselves, or their environments, are such that a residual uncertainty is always present, they should be designed to contain embedded intelligence. There is a trade-off between resources required to build machine intelligence and those needed to construct deterministic machines and their environments.

The usual sources of uncertainty to which machines are exposed include:
- The occurrence of unexpected external events ie, unpredictable changes in the environment in which they operate (eg, an unexpected obstacle in front of an autonomous vehicle, or a change of order priorities in a factory).
- The occurrence of unexpected internal events (eg, a component failure).
- Incomplete, inconsistent or unreliable information available to the system for the purpose of deciding what to do next. This uncertainty may be caused by inadequate technology (eg, low quality of sensors or ineffective processing of data obtained through sensors) or by the speed at which unexpected events occur (eg, a brief appearance of the face of an intruder in the viewing range of a security camera).

3. LEVELS OF INTELLIGENT BEHAVIOUR

As a first step towards developing design specifications for intelligent machines and systems let us classify the external behaviour of machines according to their ability to handle uncertainty.

3.1 Programmed Behaviour

Programmed behaviour is exhibited by artefacts capable of achieving specified goals or sustaining desired behaviour only under *predictable conditions*. The whole Western economic wealth was built on production lines and automated machines exhibiting programmed behaviour and characterised by precision and repeatability. It is now increasingly difficult and expensive to construct rigid, deterministic operational worlds for machines (such as a mass-production factory) and, as a consequence, the demand for conventional automated machines is bound to decline.

3.2 Proto-Intelligent behaviour

Proto-Intelligent behaviour is exhibited by artefacts (and biological systems) capable of achieving specified goals or sustaining desired behaviour under *well defined variable conditions*. Many artefacts, from thermostats to auto-pilots, and biological systems such as plants, can cope with such conditions. I have used the term Proto-Intelligence to describe *self-regulation*, the most elementary behaviour that may appear externally as intelligent. It denotes the capability of a system to achieve and sustain the desired behaviour when working in an environment which changes in time in a limited way. The characteristics that change, the range of measurable changes, and the way in which the system should respond to any particular change are known in advance. Only the timing and magnitudes of changes (within a given range) are unpredictable.

For the purposes of self-regulations a system may monitor one or several measurable physical characteristics, called variables, such as position, distance from a given object, direction of movement, speed, acceleration, pressure, liquid level, thickness and composition. Whatever the variable or the set of variables, the mechanism of self-regulation is always the same: the feedback loop. Demand for proto-intelligent machines is steadily increasing. Sensors are now being built into a variety of machines which were previously programmed to behave in a strictly predictable fashion (eg, high-speed packaging machines).

3.3 Intelligent Behaviour

Intelligent behaviour is exhibited by artefacts (and biological systems) capable of achieving specified goals or sustaining desired behaviour under conditions of uncertainty. Intelligent systems can operate *even in poorly structured environments* ie, the environments in which variable characteristics are not measurable, where several characteristics change simultaneously and in unexpected ways, and where it is not possible to decide in advance how the system should respond to every combination of events (eg, a situation in which a mobile robot must distinguish between a person and a piece of furniture in a workshop in which it operates).

Intelligence is one of those concepts that are very difficult, or maybe even impossible to understand fully, like concepts of quality [6] and excellence. For a number of years the community of Artificial Intelligence researchers has been involved in philosophical deliberations about the role of intentionality [7, 8] in understanding machine intelligence. Personally I have found much more affinity with the work of biologists such as Stonier [9] and Edelman [10].

My position is that whilst attempts to gain a further insight into the meaning of intelligence are informative, exciting and even tantalising, and should be encouraged, we must pursue, in parallel, a very important task of designing artefacts that exhibit external behaviour similar to that which is generally recognised as intelligent. Some features of such behaviour are discussed below.

Adaptability -the system is capable of changing its behaviour to accommodate unpredictable changes in its environment. A vehicle capable of spotting an unexpected obstacle and, in spite of its presence, reaching its given destination is adaptable.

Self-Maintenance - the system is capable of maintaining own state of operational readiness by means of self-diagnosing, preventive self-maintenance and self-repair by re-configuration. A satellite that identifies a faulty rocket and fires a stand-by one when required to achieve a particular action is capable of self-maintenance.

Communication - the system is capable of exchanging information with other systems with a view to exercising control over, reporting to, receiving instructions from, or engaging in competition or collaboration with other systems. Machines may be designed to operate in *collectives*, organisations similar to colonies of ants, in which every constituent element obeys precisely defined rules of collaboration, or in *societies*, organisations similar to human societies, in which artificial intelligent agents negotiate collaborative or competitive arrangements among themselves.

Autonomy - the system is capable of acting independently from other systems, including human operators. Autonomous systems operate in well defined worlds such as a world of a factory, geostationary orbit, seabed.

Learning - the system is capable of being trained to carry out certain tasks. Learning implies memorising but also context-dependent meaning. We say that an accounting program has learned something if it can recognise that the pattern of characters "petrol" means a category of travelling expenses. An autonomous vehicle has learned something if it is capable of relating the pattern of characters "corner" to a particular set of signals generated by its sensors.

Self-Improvement - the system is capable of improving its own future performance based on past performance combined with learning from other agents or human operators. Self-improvement requires collecting information on its own behaviour, analysing it, deconstructing established behavioural patterns and constructing new ones which are likely to be more effective.

Anticipation - the system is capable of predicting changes in its environment which may affect its operation. It normally involves the recognition of partially specified patterns.

Goal-Seeking - the system is capable of formulating and reviewing tactical goals with a view to achieving certain strategic advantages. To operate in an environment about which system designers have inadequate knowledge, the system should be capable of learning about the environment by experimenting with a view to formulating achievable tactical goals within constraints imposed by the overall strategy.

Creativity - the system is capable of generating useful new concepts, principles and theories, and conjecturing and testing methods and methodologies. Creative systems can interacte with humans or with a section of the real world autonomously. It is possible to envisage a situation in which a creative system attempts to change its environment (create a new world).

Reproduction - the system is capable of creating replicas of itself. Whilst reproduction of hardware systems is not of immediate concern, the need for software reproduction is overwhelming. It appears to be feasible to develop software genes loaded with instructions how and under what conditions to replicate themselves and form similar or identical programs.

At present there is no demand for comprehensive intelligent behaviour, that is, for behaviour which would encompass all the features described above. As our ability to design intelligent behaviour improves the requirements will no doubt change. The implication is that we should find ways of adding features of intelligent behaviour incrementally. The preferred organisation of intelligent systems is one that enables unplanned future improvements.

4. ARCHITECTURE OF INTELLIGENT SYSTEMS

My hypothesis is that to exhibit intelligent behaviour a system must be capable of performing three fundamental functions: *Perception*, *Cognition* and *Execution*. The relations between these three functions are depicted in Fig, 1 below.

The two major roles of Perception are (a) to collect data about the world in which the system operates (this world includes the system itself and its environment) and (b) to store and process collected data (data fusion) in order to assemble reliable information on the basis of which decisions can be made on the future system behaviour. Perception is usually associated with building and updating models of the world in which the system operates. However intelligent behaviour may be achieved without an internal world model.

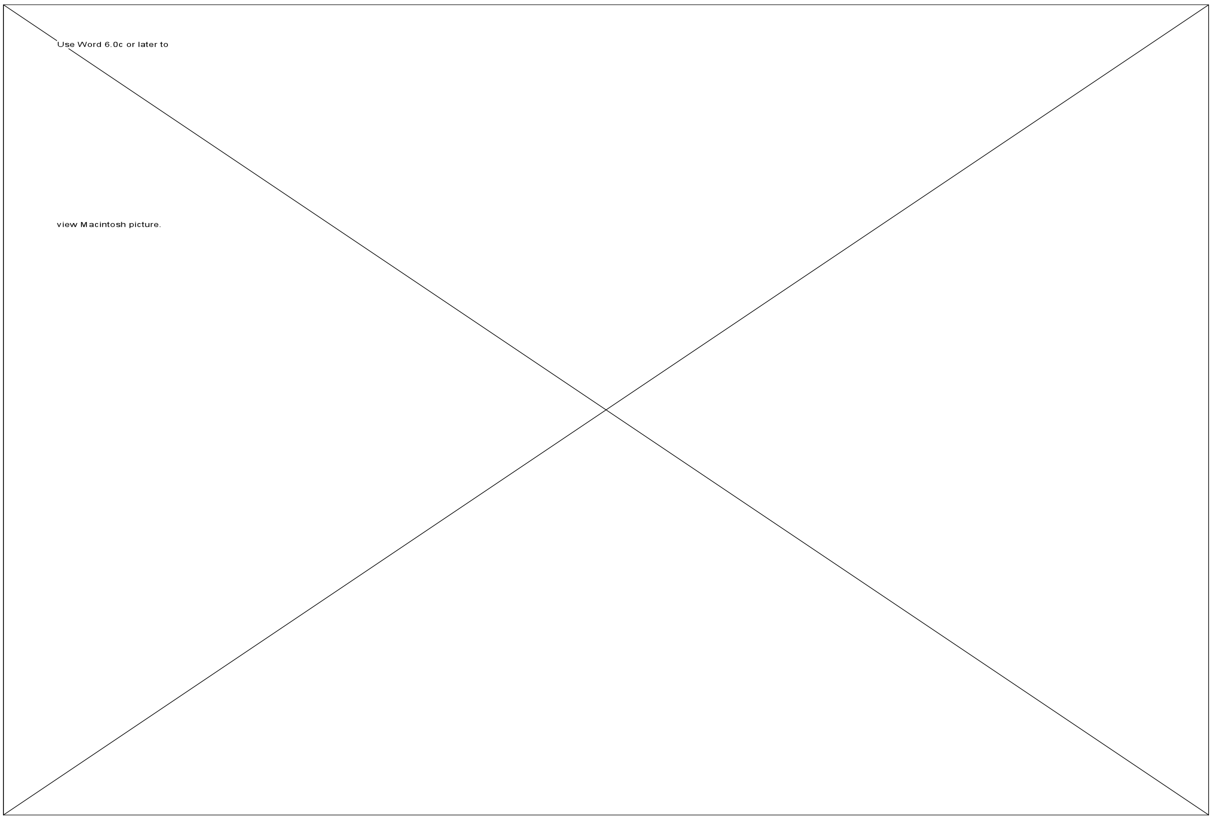

Fig. 1 Fundamental functions of an intelligent system

Cognition includes considering system goals and the current state of the world (possibly also the likely future states) and, based on this information, planning future system actions. It normally includes triggering the execution of these actions. Although some interesting examples of intelligent behaviour have been achieved without cognition [11], it is not unreasonable to expect that at least in some cases there will be a need for strategic reasoning. Systems without cognition react on external inputs: a behaviour similar to that of human organisations which rely exclusively on market forces.

Execution is mainly concerned with controlling particular behaviours. It could be initiated from cognition, to implement elements of a long-term strategy or directly from perception eg, when there is an emergency and a requirement to act rapidly.

There are many possible ways of organising these functions to achieve intelligent behaviour. From an engineering perspective the key consideration is that the resulting system must be cost-effective to implement, sell, operate and service. This implies that criteria are: an acceptable cost, weight, size and lead time; modifiability; reliability; safety; appearance; social and legal acceptability; the ease of use and ease of servicing.

Conceptually the simplest solution is a centralised architecture with perception, cognition and execution functions implemented as separate but interconnected subsystems. However, from the engineering point of view centralised architecture is not feasible. For example, the complexity of a centralised perception subsystem for an intelligent factory would be difficult to imagine. Even for a single autonomous vehicle working in a factory such architecture is not really practical.

The usual approach to reducing complexity is to adopt a multi-level hierarchical architecture with perception, cognition and execution functions distributed at various levels of the hierarchy. There are many intelligent systems of this kind under development. However, hierarchies have a major disadvantage and that is their rigidity. Evidence is mounting that hierarchies are not suitable for worlds characterised by frequent changes.

A number of very successful prototypes of intelligent machines have been constructed using Brooks' layered architecture. Brooks is an outspoken advocate of the new approach to artificial intelligence that does not rely on building large knowledge bases and reasoning [11].

5. THE CONCEPT OF AUTONOMOUS INTELLIGENT AGENTS

Back in 1985 Minsky wrote a seminal work, The Society of Mind [12]. His idea that mind is a society of agents that collectively generate our behaviour without any need for centralised control is immensely powerful and yet simple and plausible. By now agents are among the most popular topics in AI [13].

Let me describe an autonomous vehicle with distributed intelligence based on the metaphor of intelligent agents designed to service a factory cell. To operate according to expectations the vehicle must *carry loads between stores and various machines, move, navigate, recharge its batteries and maintain itself in a state of readiness*. Imagine that an agent is made responsible for each of the above functions, an agent being a computer program that can exchange messages with other programs and reason about the contents of these messages.

A specification for such an arrangement could be as follows.

- A team of five agents is assigned to plan and control behaviour of the vehicle.
- Each agent in this team is given responsibility for initiating and controlling an aspect of vehicle behaviour, that is,
    - the Driver moves the vehicle with appropriate speed in the appropriate direction,
    - the Navigator navigates among various obstacles,
    - the Maintainer monitors batteries and recharges them when necessary and monitors critical components of the vehicle and ensures that failures are anticipated.
- Another agent, the Scheduler, is given responsibility for scheduling the vehicle.
- The fifth agent, the Bookkeeper, takes care of recording, keeping accounts and reporting on all system activities.
- All decisions are made by negotiation among Agents Stakeholders (those agents whose work may be affected by consequences of a particular decision). For example,
    - the Driver and the Maintainer negotiate when to stop the vehicle for recharging batteries and for preventive maintenance,
    - the Driver and the Navigator negotiate how to cope with unexpected obstacles, and

- the Scheduler negotiates with agent Schedulers of other intelligent machines how to keep the vehicle busy and optimise the overall performance of the factory cell.

- A protocol is established to regulate negotiations and specify non-negotiable categories such as safety. As experience accumulates, agents may agree to modify protocols and thus improve the overall performance of the vehicle.

In such a scheme the factory cell is a system consisting of intelligent machines negotiating with each other how best to achieve specified goals. Each intelligent machine, in turn, is controlled by a team of intelligent agents. Agents can be designed using current artificial intelligent technology: knowledge-based systems, neural networks, genetic algorithms and fuzzy logic. Since each agent is a relatively small artificial intelligence program, many difficulties associated with large knowledge bases can be avoided.

The novelty of this approach is in replacing hierarchical architectures with network configurations in which nodes are capable of negotiating how to achieve specified goals without any centralised control. Even more important is the “collective intelligence” of the society of agents which represent an *emergent* property. A team of agents, like a human team, exhibits certain features that are not attributable to individual members. These features *emerge* from interactions of agents and depend on the nature of protocols governing mutual relationships. Liberal protocols enable unexpected modes of interaction which may result in original emergent behaviours.

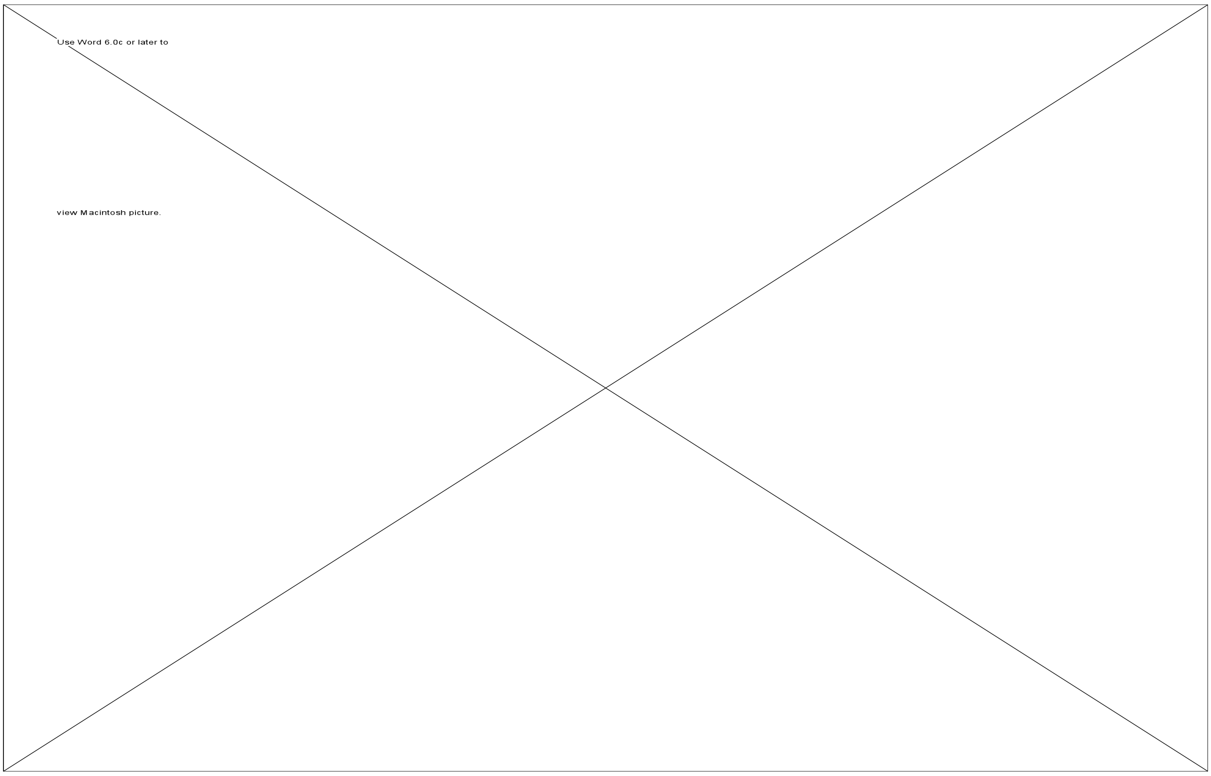

Fig. 3 A Team of agents

6. CONCLUSIONS

Global economic competition drives the development of intelligent machines and intelligent organisations. Short manufacturing runs, short lead times and demand for highly customised goods and services favour flexible, responsive manufacturing systems, concurrent engineering teams and global supply-chain partnerships. Distributed factories, virtual design studios, autonomous machines and global intelligent systems are likely to dominate the industrial scene in the next century.

The key to developing effective intelligent machines for practical applications is a simple but powerful intellectual framework which concentrates mind on important issues:

- how much uncertainty should be allowed in the operational world of a machine?
- what is the minimum amount of knowledge required to be stored in the machine to enable it to cope with its environment?
- what kind of sensors and associated information processing capabilities are required to reduce a sizeable proportion of the initial uncertainty during normal machine operation?
- what level of intelligence is required to handle residual uncertainty?
- which architecture will be best suited for the application at hand?

Trends are:

- designing intelligent machines with higher levels of intelligence (self-maintenance, learning, self-improvement);
- selecting architectures that are flexible and allow incremental development (centralised and hierarchical architectures are being replaced by layered and network architectures);
- interconnecting machines into systems and “societies of agents” (to take advantage of “collective intelligence”).

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