Characterising Plans as a Set of Constraints – the <I-N-OVA> Model – a Framework for Comparative Analysis

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1 Motivation

The <I-N-OVA> (*Issues – Nodes – Orderings/Variables/Auxiliary*) Model is a means to represent plans as a set of constraints. By having a clear description of the different components within a plan, the model allows for plans to be manipulated and used separately to the environments in which they are generated.

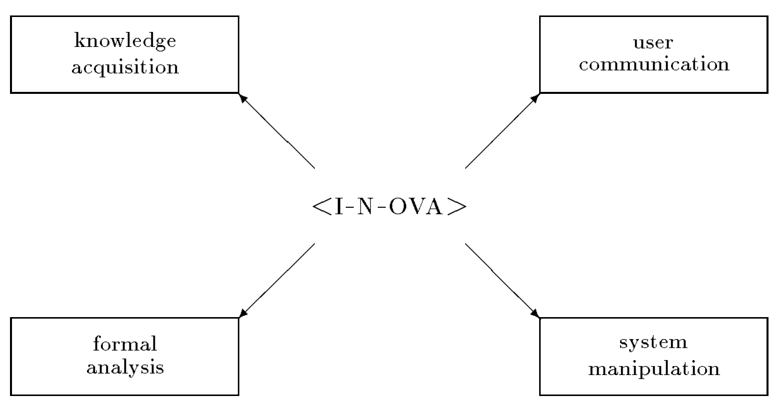

Figure 1: Roles for <I-N-OVA>

As shown in figure 1 the <I-N-OVA> constraint model underlying plans is intended to support a number of different uses of plan representations:

- suitability for automatic manipulation of plans and to act as an ontology to underpin such use.
- suitability for human communication about plans.
- suitability for principled and reliable acquisition of plan information.
- suitability for formal reasoning about plans.

These cover both formal and practical requirements and encompassing the needs of both human and computer based planning systems.
Our aim is to characterise the plan representation used within O-Plan [8],[34] and to more closely relate this work to emerging formal analyses of plans and planning. This synergy of practical and formal approaches can stretch the formal methods to cover realistic plan representations as needed for real problem solving, and can improve the analysis that is possible for production planning systems.

2 Representing Plans as a Set of Constraints

A plan is represented as a set of constraints which together limit the behaviour that is desired when the plan is executed. Work on O-Plan [8],[34] and other practical planners has identified different entities in the plan which are conveniently grouped into three types of constraint. The set of constraints describe the possible plan elaborations that can be reached or generated as shown in figure 2.

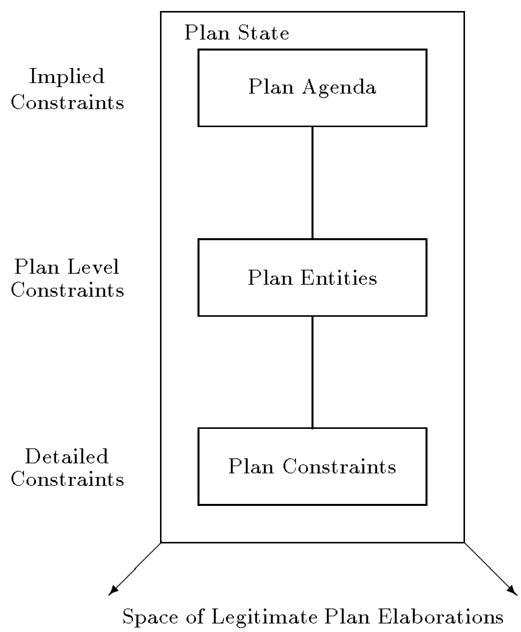

Figure 2: Plan Constraints Define Plan Space

The three types of constraint in a plan are:

1. Implied Constraints or "Issues"[1] – representing the pending or future constraints that will be added to the plan as a result of handling unsatisfied requirements,

[1] We have previously used a variety of different names for these constraints: *Agenda Entries* reflecting

dealing with aspects of plan analysis and critiquing, etc. The implied constraints are the issues to be addressed, i.e., the "to-do" list or agenda which can be used to decide on what plan modifications should be made to a plan by a planner (user or system).

2. Plan Entities or Plan Node constraints - the main plan entities related to external communication of a plan. They describe a set of external names associated to time points. In an activity planner, the nodes are usually the actions in the plan associated with their begin and end time points. In a resource centred scheduler, nodes may be the resource reservations made against the available resources with a begin and end time point for the reservation period.

3. Detailed Constraints - associated with plan entities and representing specialised constraints on the plan. Empirical work on the O-Plan planner has identified the desirability of distinguishing two special types of detailed constraint:

   - Ordering or Temporal Constraints (such as temporal relationships between the nodes or metric time properties).
   - Variable Constraints (co-designation and non-co-designation constraints on plan objects in particular).

   These two constraints are highlighted since they may form part of other constraints within a temporal reasoning domain such as occurs in planning and scheduling problems. Knowing that these constraints have such cross "associations" has been found to simplify planner system design of constraint handling mechanisms and ease implementation issues [29],[30].

   Other Detailed Constraints relate to input (pre-) and output (post-) and protection conditions, resources, authority requirements, spatial constraints, etc. These are referred to as:

   - Auxiliary Constraints.

   Auxiliary Constraints may be expressed as occurring at a time point (referred to as "point constraints") or across a range of the plan (referred to as "range constraints"). Point constraints can be used to express input and output constraints on nodes or for other constraints which can be expressed at a single time point. Range constraints relate to two or more time points and can be used to express protection intervals, etc.

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the chosen method of representation in O-Plan; *Flaws* as suggested by Sam Steel in the mid 1980s and reflecting the original concentration of representing the outcome of plan critics which found interactions in the teleological structure which had to be corrected; *To-do list entries* reflecting common usage in business; *Pending Processing Requirements* reflecting the notion that they implied future plan manipulation or constraints; and others. We have settled on *Issues* suggested by Craig Wier in 1994 as being an easily understood term that reflects both the need to handle problems and the positive opportunities that present themselves.

3 The <I-N-OVA> Model

A plan is represented as a set of constraints of three principal types. To reflect the three main types of constraint identified and their differentiation in the model, the constraint set for a plan is written as <I-N-OVA> (*Issues – Nodes – Orderings/Variables/Auxiliary*). I stands for the the issues agenda or implied constraints, N for the node or plan entity constraints, and OVA for the detailed constraints held as three types (O for ordering constraints, V for variable constraints, and A for the other auxiliary constraints).
The auxiliary constraints are given 4 types: Authority, Conditions, Resources and Other and all may be stated as point (related to a single time point) or range (related to two or more time points) constraints. Sub-types are possible for any of the Auxiliary Constraints and the nature of these reflects on-going work on knowledge modelling for planning and scheduling domains (e.g., [28], [33]).
The <I-N-OVA> constraint model for plans thus contains a hierarchy of constraint types and sub-types as follows:

```
Plan Constraints
  I   - Implied Constraints
  N   - Node Constraints relating to
                a set of time points
  OVA - Detailed Constraints
        O - Ordering Constraints
        V - Variable Constraints
        A - Auxiliary Constraints
            - Authority Constraints
              - subtypes
            - Condition Constraints
              - subtypes
            - Resource Constraints
              - subtypes
            - Other Constraints
              - subtypes
```

The node constraints in the <I-N-OVA> model set the space within which a plan may be further constrained. The issues and OVA constraints restrict the plans within that space which are valid.
The <I-N-OVA> model currently assumes that it is sufficiently general for each node (referred to as N constraints) to be associated with just two time points. One representing the begin of the node and the other representing the end of the node. Further research may indicate that a more general multiple time point association of nodes to time points may be necessary.
Hierarchical or abstraction level modelling is possible for all constraint types within the <I-N-OVA> model. To reflect this possibility, an <I-N-OVA> model which is described

hierarchically or with levels of abstraction will be referred to a Hierarchical <I-N-OVA> model. This will be written as Δ-<I-N-OVA>.
The Δ is a triangle pictogram symbol used to represent hierarchical expansion. It can be written in an alternate all character version as H-<I-N-OVA>.

4 The Triangle Model of Activity

The <I-N-OVA> auxiliary constraints incorporate details from the Triangle Model of Activity used to underpin the Task Formalism (TF) domain description language [32] used for O-Plan [8],[34]. The Triangle Model seeks to give a clear description of activities, tasks and plans in a common framework that allows for hierarchical decomposition and time relationships along with authority, pre- and post-conditions, resources and other constraints. The Triangle Model of Activity can be used as a basis for planning domain modelling and for supportive task description interfaces.
The aim in the Triangle Model is to simplify some of the notions from expressive plan and activity representations from AI planning and to relate them better to existing systems engineering requirements capture and modelling languages and methods (like SADT [24], IDEF [20], CORE [9], HOOD [13], etc.).

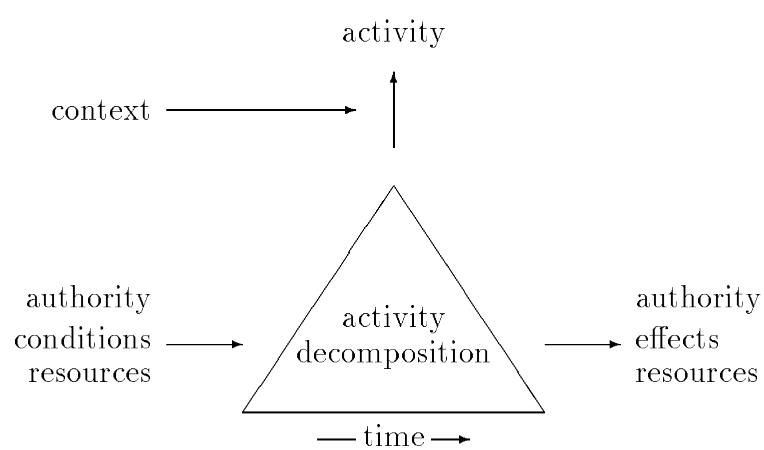

Figure 3: O-Plan Triangle model of Activity

Figure 3 shows the Triangle Model of Activity. The vertical dimension reflects action decomposition, the horizontal dimension reflects time. Inputs and outputs are split into three principal categories (authority, conditions/effects and resources). Arbitrarily complex modelling is possible in all dimensions. Types and sub-types are used to further differentiate the inputs and outputs, and their semantics.

"Entry" to the model can be from any of the three points in the triangle: from the top vertex to ask for activity expansions or decompositions, from the right to ask for activities satisfying or providing the output requirement (authority, goal or resource). These two sides are used mostly by AI planners to date. The third side from the left can reflect non-intended triggering conditions for an action and will be needed when improved independent processes are modelled as in the EXCALIBUR [10] extension to Nonlin [26].
The activity decompositions shows the expansion of the activity to a greater level of detail if that is modelled. It can include details of protection conditions that span points within a decomposition.
Variables may be referred to in an activity description. Differentiation between those variables used in the external specification (outside the triangle) and those only used within the activity decomposition (internal to the triangle) is possible.
The O-Plan time model defines a set of time points which can be related to an absolute start of time (for metric time statements) or which can be related to one another (for relative time relationships). Temporal relationships between an activity (referred to as *self*) and the sub-activities within a decomposition may be stated with reference to the two "ends" of any activity. Arbitrarily complex temporal relationships (e.g., [2]) are possible in the general Triangle Model
The "intentions" or "rationale" behind the use of a particular activity can be related to the features of this triangle model. Causality or teleology modelled via activity pre-conditions/post-conditions has been used in AI planners for many years to record the plan rationale (e.g., in Nonlin [26]). In the richer model now in use in O-Plan, rationale in terms of resource usage and supply or authority requirements or delegation may also be stated. This makes it possible to use a uniform approach to the modelling of authority, product flow and resource requirements.

5 Relationship of Triangle Model to O-Plan TF Schemas

The Triangle Model of activity maps directly to an O-Plan Task Formalism (TF) schema. TF is the domain description language for O-Plan. The following shows the components of a simplified O-Plan TF schema. "..." indicates the detailed part of each component. Further detail is available in [32].

```
schema <schema_name>;
   ;;; public information
   vars                     ... ;
   expands                  ... ;
   only_use_for_authority   ... ;
   only_use_for_effects     ... ;
   only_use_for_resources   ... ;
```

```
   ;;; private information
   local_vars              ... ;
   vars_relations          ... ;
   nodes                   ... ;
   orderings               ... ;
   time_windows            ... ;
   authority               ... ;
   conditions              ... ;
   effects                 ... ;
   resources               ... ;
   other_constraints       ... ;
end_schema ;
```

6 Domain Operators, Tasks and Plans

Figure 4 illustrates the dependency relationships between Domain, Task and Plan knowledge. Tasks and Plans are both based upon the entities in the Domain model. Plans also are elaborations of a specific Task.

- *Domain* knowledge, describes "fixed" things like facilities, organisational relationships, procedures, systems, products and the types of resource available. This knowledge is likely to be highly reusable for many different requirements.
- *Task* knowledge, describes the objectives such as the goal or goals which the plan is designed to achieve, the activity to be carried out, the actual resources available, the time available, etc.
- *Plan* knowledge, describes a particular way (currently under exploration) in which the specified task objectives can be achieved in the current domain.

<I-N-OVA> is intended to underpin domain, task and plan modelling needs in a planning system whether human, computer or mixed agents are involved. Communication between planning agents in O-Plan takes place via Plan Patches [27] which are also based on the Triangle Model of Activity and the <I-N-OVA> constraint components.

7 Relationship of Triangle Model to Structured Analysis and Design Techniques

There is a deliberate and direct mapping between the O-Plan Triangle Model of Activity and the <I-N-OVA> Constraint Model of Plans to existing structured analysis and diagraming methods such as IDEF, R-Charts, etc. Other researchers have recognised the

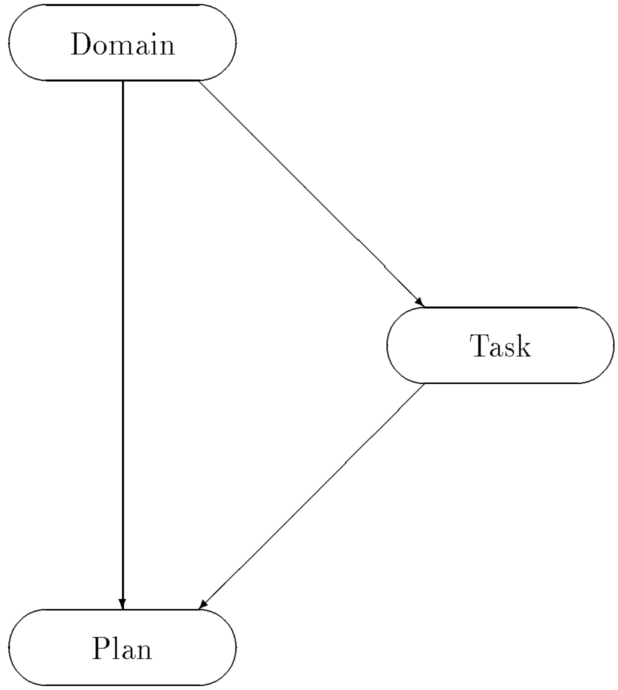

Figure 4: Dependencies between Domain, Task and Plan Knowledge Partitions

value of merging AI representation concepts with structured analysis and diagramming techniques for systems requirements modelling [6].

IDEF0 [19] is a functional modelling method and diagraming notation that has been used for modelling processes[2]. Figure 5 shows the basic component.

IDEF modellers usually use "control" for authority related triggers and "mechanism" to reflect resource availability. A criticism of IDEF is the lack of direct support for modelling the different types of output and their intended destination. Experienced IDEF modellers use the arc labels, naming conventions and the "notes" system in an IDEF support "kit" to encode this information.

R-Charts [35] are one of the ISO approved diagraming conventions for program constructs (ISO/IEC 8631 [14]). Figure 6 shows the basic component which explicitly acknowledges the importance of control (or authority) related outputs.

The O-Plan triangle model represents all three types of input and output more uniformly and directly and will allow for improved support tools.

[2] IDEF3 [20] is a later more comprehensive IDEF method specifically targeted at the modelling of processes.

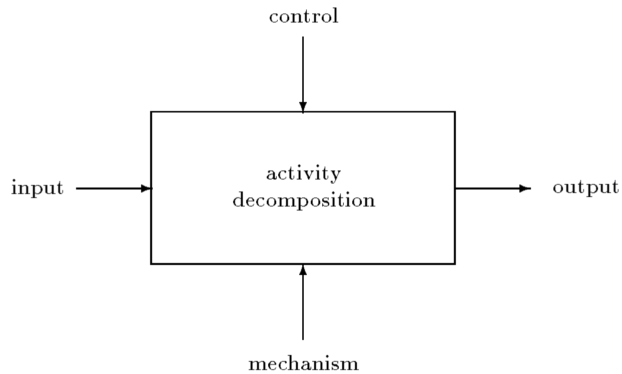

Figure 5: IDEF0 model

8 Relationship to Other Work

A general approach to designing AI-based planning and scheduling systems based upon partial plan or partial schedule representations is to have an architecture in which a plan or schedule is critiqued to produce a list of issues or agenda entries which is then used to drive a processing cycle of choosing a "plan modification operator" and then executing it to modify the plan state. Figure 7 shows this graphically.

This approach is taken in systems like O-Plan [8],[34], RT-1 [3], OPIS [25], DIPART [23], TOSCA [5], etc. The approach fits well with the concept of treating plans as a set of constraints which can be refined as planning progresses. Some such systems can act in a non-monotonic fashion by relaxing constraints in certain ways.

Having the implied constraints or "agenda" as a formal part of the plan provides an ability to separate the plan that is being generated or manipulated from the planning system itself. The benefits were first noted by McDermott [21] and are used as a core part of the O-Plan design.

A recently described approach to Mixed Initiative Planning in O-Plan [31] proposes to improve the coordination of planning with user interaction by employing a clearer shared model of the plan as a set of constraints at various levels that can be jointly and explicitly discussed between and manipulated by user or system in a cooperative fashion.

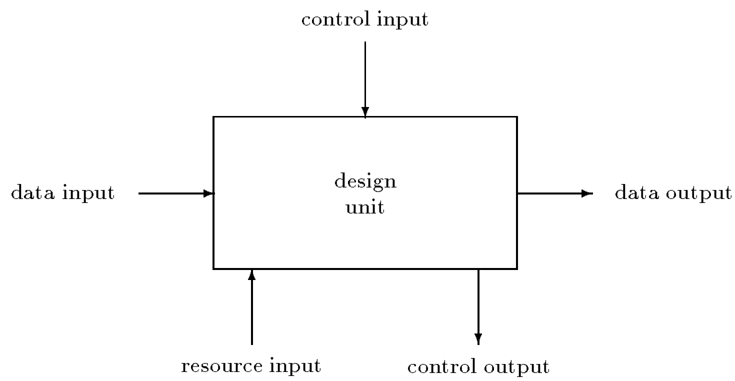

Figure 6: R-Chart Model

9 Relationship to Formal Studies of Plans and Planners

The Nonlin QA Algorithm [26] establishes the modifications that are needed in terms of plan step ordering and variable binding to ensure that a given statement has a required value at a given point in a partially ordered network of nodes. This has been a basis for the formal work by Chapman [7] on the Modal Truth Criterion. However, the MTC uses a simplification of the plans being represented in practical planners such as Nonlin [26], O-Plan [8],[34] and SIPE [37]. It took a non-hierarchical view and ignored specialised domain knowledge of activity condition types and constraints. Many of these were those very features that allowed planners like Nonlin and SIPE to solve problems at a scale that was beyond the more theoretically based planners. Drummond [12] explains that formal approaches have concentrated on goal achievement aspects of planners in a simplified environment that is not representative of the approaches actually taken in practical planners.

Recently however, formal representations have begun to address issues of realistic plan representations and to model hierarchical planning [4],[18],[22],[38]. In particular, Kambhampati has described a formal truth criterion for plans which are represented with greater levels of realism. He describes plans as a 5 tuple [16]:

```
<S, O, B, ST, L>

S  a set of plan steps or nodes
ST a symbol table mapping each plan step
   or node to a domain operator
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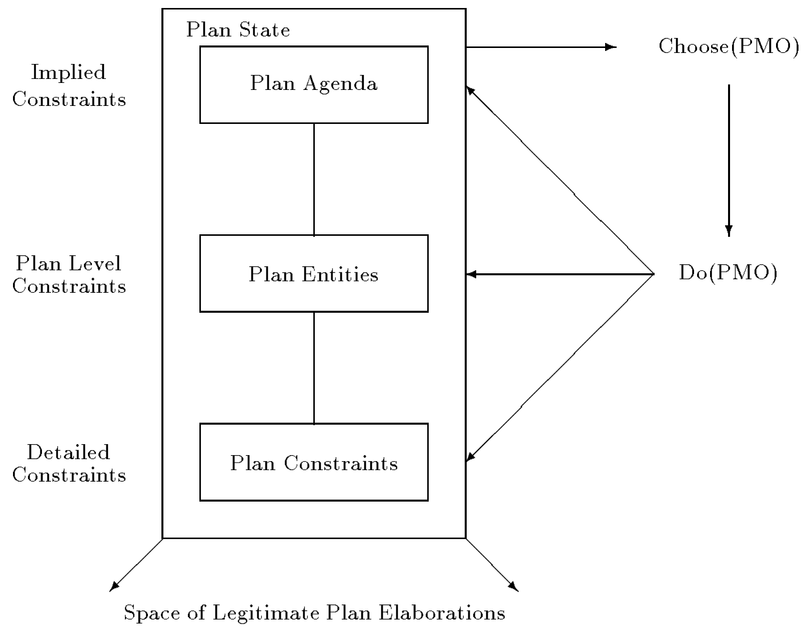

Figure 7: A Framework of Components in a Planning/Scheduling System

```
O  a partial ordering over S
B  a set of variable binding
   co-designation and
   non-co-designation constraints
L  a set of auxiliary constraints
   (mainly intended for pre- and post-
   conditions)
```

This representation can be related directly to the N (S and ST) and OVA (O, B and L) parts of the <I-N-OVA> model[3].
Hendler and Kambhampati are also studying hierarchical approaches to formal methods in planning [17],[18]. Work is underway by Kambhampati and by Young [39] to understand aspects of the use of "condition types" [33] used to provide domain semantic information to Nonlin, O-Plan and other practical planners.

[3] The use of the term "Auxiliary Constraints" in <I-N-OVA> was adopted as a means to relate to this formal work. In fact the <S, O, B, ST, L> constraint set acts as a refinement filter on all possible plans, whereas <I-N-OVA> also defines the candidate set from which the solutions may come. This needs further study to relate the two approaches.

10 A Framework for Further Study

To provide a framework for further study, the following classification of models related to <I-N-OVA> is provided.

	partial plan	partial plan with issues
single level model	<N-OVA>	<I-N-OVA>
hierarchical model	Δ-<N-OVA>	Δ-<I-N-OVA>

A base model <N-OVA> is used to represent a basic plan without hierarchy or abstraction modelling and not including implied constraints (the issues agenda). The other models extend this basic model along these two dimensions[4]. They are all supersets of <N-OVA>, and are collectively termed *Super*-<N-OVA> models.

The <N-OVA> element most closely relates to the model being studied by Kambhampati today [16]. The Δ-<I-N-OVA> element is the closest to the plan representation used within O-Plan today.

11 Summary

The <I-N-OVA> Constraint Model of Plans and its relationship to the O-Plan Triangle Model of Activity has been described to assist in more closely relating new work in formal descriptions of plans and planners to practical work on realistic planning systems. <I-N-OVA> is intended to act as a bridge to improve dialogue between the communities working in these two areas and potentially to support work on automatic manipulation of plans, human communication about plans, principled and reliable acquisition of plan information, and formal reasoning about plans.

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[4]Non-determinism is a property of the system (human or computer based) which manipulates the plans and is not necessarily represented in the constraint model. However, it is usual to include explicit dependency information in a plan via constraints to support non-monotonic planners. This may indicate that it would be useful to define a third dimension to this framework for further study.

process modelling, synthesis, analysis and modification. O-Plan work is funded as part of the $40 million US ARPA and USAF Planning Initiative which is developing next generation planning, command and control support infrastructure relevant to US military logistics. AIAI is pursuing its approach to the use of knowledge rich plan and process representations in commercial applications though its collaboration in the Enterprise project. Enterprise is a consortium including AIAI, IBM, Unilever, Logica and Lloyds' Register and is the largest project supported by the UK government's Intelligent Systems Integration Programme.

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