Non–Monotonic reasoning about and within spatial images

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Abstract

One of the paradigms of remote sensing imagery is the quick and accurate classification and interpretation of images.

Reasoning about space always implies reasoning with and about spatial features and relations among them. Actually, spatial reasoning seems to include two different tasks: visual interpretation of geographic maps (topographic and thematic maps) and use of analytic, often statistical tools.

Some efforts have been done to develop knowledge-based systems for automatic interpretation of spatial images, but often the accuracy achieved by such systems is not generally acceptable. Moreover, such systems do not have a declarative (simple and non-operational) semantics, which makes those systems difficult to use, maintain and improve.

Aspects concerning concepts based on geographic objects and relations among them, as well as reasoning with them are still missing.

The image interpretation task is a trial and error, user dependent process, with personal perspectives for solving local inconsistencies between the image (digital values) and the analyst expertise, most of the time based on *common–sense* and *intuition*. Validation is always necessary with field data or alternative data sources such as aerial photographs, to assess the accuracy of the results. However, for some tasks, validation is not possible or even desired. In these cases, the final classification is very user-knowledge dependent and its confidence is greatly supported by personal assumptions and beliefs.

Here we propose a logic-based framework to reason with (and about) spatial objects. This framework has different hierarchic levels ranging from the lowest - pixel level - to the highest -concept level - where highly composite objects may be defined (a town as a buildings agglomeration or a river as a line with a blue color), as well relations among those objects.

1 Introduction

Digital images are becoming one of the most valuable and useful data sources for an increasing set of subjects and goals. Examples include diagnosis in medicine, urban administration, design in architecture and engineering and military target recognition. Recently, Geographical Information Systems (GIS) from the field of geography have being enriched with digital-image processing technology besides alfa-numeric databases.

The interpretation of geospatial images is a complex task due to its complexity and diversity of objects within it involving object recognition and scene analysis tasks [DH73] which have been pursued by different approaches, namely pattern recognition techniques based on texture and shape analysis [SM92], and statistical classification algorithms based on spectral similarity analysis [Ric86].

Research in the field of spatial analysis are mainly related to the clustering problem, being the statistical spatial association measures [Ric86], [GW92], [Ans93], [Cre92] and artificial intelligence techniques - neural networks [Civ91], [FG93], [MKR95], expert systems [Wha87], [Civ89], [WB91] and fuzzy logic [Wan90], the most widely used. The study of spatial dependence of one attribute to another, has exclusively relied on statistics, implying an adaptation of existed methods to the reality of spatial autocorrelation. The consideration of time in spatial data has been accounted for different types of models (geostatistical, lattices, and point patterns) by [Cre92], but its integration within the GIS technology is still missing.

Validation is always necessary with field data or alternative data sources to assess the accuracy of the results. Moreover, in some research or practical tasks the validation is not possible (e.g. the interpretation of a ten years old image) [Sei93] and even not desired due to resource constraints (e.g. the update of land cover maps). In these cases results are very user-knowledge dependent and its confidence is greatly supported by personal background and assumptions about the ground truth. The existing techniques do not capture this user reasoning process, which guides the interpretation task and is a decisive factor for the understanding and acceptance of the interpretation task results.

Here, we propose a logic-based approach to assist in the task of Geospatial Image Interpretation which intends to integrate the different conceptual levels of image analysis: pixel level (e.g. false colored pixels from a satellite image), cluster level (e.g. pixels with blue color), geometric level (e.g. a line) and concept level (a river). We present its formalization at the lower level (i.e. pixel level) using a toy example. Some experimental results on the use of conceptual clusters relating to urban areas in a SPOT satellite image illustrating the interpretation process are presented in [SA94] and [SCN96].

It has been considered that, the long term goal of the integration of AI in image analysis is the development of systems that can interact with a human analyst at a highly symbolic level, which implies a formal definition of the problem, as well as the formalization of the reasoning process. Formalization of the user reasoning over an image brings some useful contributions for the GIS goals, besides its unique interest on formal reasoning from an AI perspective. In fact, the formalization of reasoning enforces the user to think structurally and to identify the mental and knowledge assumptions the user does to make conclusions, which is a process of self-validation. If a sequence of reasoning steps is always performed to a specific goal, these steps can be automated and the spatial analysis becomes more efficient from the user perspective, in the sense of less time consuming.

To accommodate a spatial reasoning formalism, a formal representation of spatial data has to be developed. Within this context, we consider spatial data at different levels as the elements the user uses to perform spatial reasoning, being the image elements, such as pixels, sets of similar pixels, and geographic objects the most widely used.

For that purpose Artificial Intelligence techniques, namely those based on logic programming, seem to be quite appropriate since they allow the user to identify, explore, and integrate his personal knowledge and reasoning about geographic features. Questions such as negation, inconsistencies, and contradictions are logic clues needed to formal reasoning, that are well accommodated in the framework of the non-monotonic formalism [Apa93]. This fact represents an improvement in the formalization of reasoning mechanisms and thus in the efficient use of knowledge-based systems for human reasoning, which is decisive for the spatial analysis task.

2 CONCEPTUAL FRAMEWORK FOR SPATIAL REASONING

Considering the actual GIS technology, the representation of spatial knowledge (individual geographic features and composite scenes) is very primitive in the sense that it is a pictorial display resulting directly from scanning or digitizing that the user has to visualize and interpret in order to elaborate on it. Some related factual knowledge is specified and stored in a relational database, usually in numeric or string clues. The spatial reasoning task, as mentioned above, is not possible to be accommodated within this context, unless the user do it outside the GIS environment.

The long term goal of our research is to develop a system that, help human analyst at a high symbolic level, uses expert-knowledge to suggest areas for fruitful analysis, and integrate the results of the analysis into a coherent model.

Spatial Data Framework To understand the reasoning process about images one can think of an analyst in front of a map in a computer display: he/she identifies several layers of image information (cf. Fig. 1).:

- a set of pixels (e.g. false–color pixels from a satellite image);
- sets of "similar" pixels (e.g. pixels with blue color);
- a geometric object (e.g. a line);
- a geographic feature (e.g. a river).

According to this, reasoning with (and about) spatial features means to consider, from the user perspective, the perception of the geographic space as a hierarchy of information levels ranging from the lowest - pixel level - to the highest - conceptual level - where highly composite features may be defined (a *river* as a *line* construed from a *set* of pixels of *similar* colors). Fig. 1 illustrates the hierarchy we propose to accommodate spatial data framework. It is also evident from it the semantic gap existing between the cluster level and (geometric) object level.

The Reasoning Process The pixel level is a form of representation which is common to all spatial data and integration and compatibility of different types of data can be performed.

The identification of clusters at cluster level is based often on two types of distances among pixels: the geographic distance, obtained from the coordinate system, and the semantic distance related to the metric of property under analysis (e.g. reflectance values, weather conditions). There are several spatial association measures, which accommodates those distances [Ans93], but the final accepted clustering depends on the personal user knowledge and experience.

Since clustering is achieved, some attributes have to be assigned to clusters in order to get an identification according to the user's knowledge and mental model. At this step, appropriate semantics which represents properties and/or functions can be assigned to the cluster, to define geometric objects. The geometric level is a rich structure since the geographic features are now perfectly formalized for the scene under analysis.

A richer data structure can be obtained at a higher level, through the conclusion of the concept underlying the identified objects. The concept level must be independent of the scene under analysis and, in most of the situations, it is the basis for human reasoning (e.g. spatial reasoning implies to think about a river and not about a line whose color is dark blue).

Although a hierarchical framework is presented to accommodate spatial data, reasoning about spatial features is often performed at all of the considered levels. In fact, for the interpretation of an image, the analyst considers the set of pixels with similar colors (e.g. pixels with blue color), and at the same time has some idea of a specific geographic object (e.g. a line or a circle) and the associated concept (e.g. a

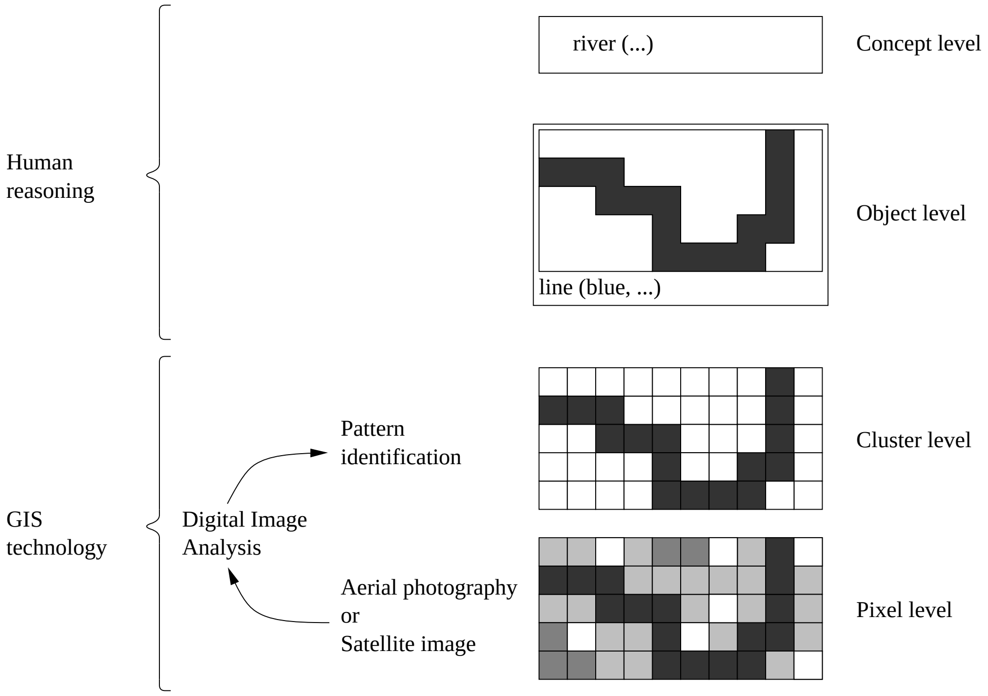

Figure 1: Framework for the spatial data reasoning.

river or a lake), in order to conclude a land cover class. Within this context, it can be stated that the reasoning formalization has to accommodate all data levels.

However, it is well known that the image classification and covering task is based primarily in analysis at the pixel level, while the conclusion of high level knowledge is supported exclusively by concepts (e.g. the river constraints agriculture can be derived as a geographic law of the local under analysis, if cultivated fields are crossed by the river in almost of the entire scene) and assessment of spatial geometry is derived rather from the object level. Thus, specific reasoning formalisms can be operationalized preferably based on a specific data level, which makes easier its understanding and edition for the user, at least at the present stage of the research work.

In this paper, a formal definition of the geographic space is proposed in order to show the use of the reasoning formalisms. In particular, the formalization of the reasoning process at the pixel level is presented, for a land cover mapping interpretation. The problem of image classification for land cover mapping is addressed and developed in [SA93].

2.1 The Framework

In this section we present a formalization of the problem of interpreting an image in order to identify a land covering. Some simplification hypotheses $\mathcal{H}$ are introduced which we will explicitly enumerate for the sake of cross-reference and future use.

Definition 1 A *LAND* is a set of geographic coordinate points (x, y) (or simply $\overline{x}$). A *cover domain CD* is a finite set of cover elements (e.g.*crop, water, house,* $\ldots$) to be assigned to particular coordinates from *LAND* and COLORS is a finite set of colors.

Definition 2 A *cover* is a mapping $LAND \to CD$ assigning to each coordinate, some (possibly none) elements from the cover domain and represented by a collection of pairs $(\overline{x}, c)$ with $\overline{x} \in LAND$ and $c \in CD$.

A cover $LAND \to CD$ is *consistent* iff it is a function, (i.e. it assigns two cover elements to no $\overline{x} \in LAND$). A cover is *total* iff $\forall_{\overline{x}} \in LAND \Rightarrow \exists_c \in CD$ such that $(\overline{x}, c) \in LAND \to CD$, (i.e. to every coordinate is assigned some element in the cover domain), otherwise it is *partial*.

The most accurate cover one may get is the one constructed by going to each coordinate point in $LAND$ and examining its actual cover (this particular cover is known in the GIS field as the *ground truth* and we denote it by $GRND$).

Another example of a cover is the one constructed from a given geospatial image received e.g. from a satellite, if colors are to be interpreted as cover elements.

Definition 3 A (satellite) image is a mapping $img : LAND \to COLORS$.

A satellite can thus be seem as a (complex) function from $LAND \to CD$ to $LAND \to COLORS$.

The general **image interpretation problem** may thus be described as:

> Given a geographical area $LAND$ with a cover $GRND$, and a mapping $img : LAND \to COLORS$ received from a satellite find a mapping $interp : LAND \to CD$ such that:
>
> - $interp$ is total;
> - $interp$ is consistent;
> - $interp$ is definite;
> - $interp \equiv GRND$.

It is worthwhile to notice that $GRND$ is always a *consistent* mapping, although it may be not (completely) known. Furthermore it is always a total function but is (in general) noisy, i.e. there is no substitution of colors by cover elements such that applied to $LAND \to COLORS$ returns back $GRND$.

When interpreting an image the user “tries” to assign cover elements to pixels in the image. In general there may be other sources about $LAND$ (e.g. a mapping from a geographic information system) providing additional informational about $LAND$ such as altitude, slope, etc., which can be easily incorporated into the framework as additional adequate mappings. For the sake of simplicity of presentation and without loss of generality we assume that:

$\mathcal{H}$ **1** The unique source of information is a (satellite) bitmap $img : LAND \to COLORS$.

Due to $\mathcal{H}_1$ the user's reasoning can be expressed by rules of the form[1]:

$$img(\overline{x}_i, c_l), \ldots, \neg img(\overline{x}_j, c_m) \to img(\overline{x}_k, c_n) \quad (1)$$

Interpretation rules of the form (1) denote structural interrelating information among and only about the pixels in the image: intuitively it expresses that when the color of $\overline{x}_i$ is c_l and the color of $\overline{x}_j$ is not c_m then the color of $\overline{x}_k$ has to be c_n.

An *interpretation process* IR (or simply *a program*) is a set of rules of the form (1). A program IR mimics the way the user reasons about images (pixels in this case). A given mapping $LAND \to CD$ denotes a "good" covering wrt. IR

[1]On site information about $\overline{x}$ may be represented with a rule say $map(\overline{x}, agriculture) \leftarrow true$, or simply $map(\overline{x}, agriculture)$.

iff every rule in IR is "satisfied" by the $LAND \rightarrow CD$ and every $(\overline{x}, c) \in img$ is "explained" by a rule in IR. It is possible that given an image, the user accepts it as a good cover for the $LAND$ under consideration, since the cover elements assigned to pixels in the image are in some sense in accordance to what is "expected" by the user. We express it as follows:

Definition 4 A mapping img is:

- *acceptable* wrt. program IR iff $IR(img) \subseteq img$;
- *supported* by IR iff $\forall m \in img \exists r \equiv m \leftarrow body \in IR$ and every element in the *body* is also supported;
- *coherent* wrt. IR iff it is both acceptable and supported;

and finally, a coherent mapping img is *definite* iff for every img' such that $IR(img') = img' \Rightarrow img' = img$.

This will only solve the image interpretation problem iff $IR(MAP) = GRND$, i.e. if the user knows $GRND$, otherwise the system will provide alternative complete interpreted images. The variety of rules which may be used in IR is enormous, and have different scope and applicability (e.g. location rules, zone rules, neighborhood rules and so on [Tom90]). Nevertheless from the point of view of the applicability (i.e. generality) of those rules, either they can be applied to every region expressing some property which is independent from any particular region to be considered or they express some property which is verified almost everywhere (i.e. for every $\overline{x}$ in a given image) but may fail to be verified for particular regions. Thus, we consider two main sorts of rules:

AIR *absolute* inference rules which are applicable everywhere (any $\overline{x}$) applicable (i.e. are valid rules for every region) to make inferences, and its use always contributes to produce an acceptable cover, e.g. $\neg(cover(\overline{x}, agricul) \wedge (slope(\overline{x}) \geq 20))$. Another such rule is the rule stating that every cover must be consistent, i.e. $\neg(cover(\overline{x}, c_1) \wedge cover(\overline{x}, c_2) \wedge c_1 \neq c_2)$.

DIR *defeasible* rules which are applicable to almost every region to make inferences, but which may fail to be applicable to particular regions, and thus triggered out.

These sets of rules provides a tool for the user to test plausibility of different interpretations, which is a useful tool (also noticed by [McK87]) when the user no longer has access to ground truth for validation.

Nevertheless, the set IR ($IR = AIR \cup DIR$) act as a guide for a first interpretation of a given mapping. The validation of $int : LAND \rightarrow CD$ (that means, to establish $int \equiv GRND$) is decided by the analyst: he (she) is satisfied with the result or not, and in this case, the ground truth data or other source must be used. This raises the question of accuracy assessment of the interpreted image. A measure based on the number of inconsistencies and its location (the inconsistencies ever occur in the same places or are generalized all over the image?) can be built. However, this point has not addressed yet, being the accuracy dependent on the user personal assessment.

Several formalisms have been developed and applied successfully to commonsense situations [PAA93], and operational semantics are proposed in [Apa93] based on non-monotonic formalisms.

It is interesting to notice that one particular aspect the system exhibits when regarded as a symbolic system, is the ability to realize that a given image may be consistent with a set of interpretation rules, or more interesting is the recognition that only part of an image may be consistent with a given interpretation. This provides a partial answer to the question: How acceptable is a given image?.

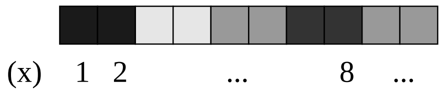

Figure 2: The ground truth – $GRND : LAND \rightarrow CD$

3 An Example

We present now an example developed at the pixel level, but which will be extended on future work to sets of pixels with the same color (clusters), as well as geometric and concept. First we introduce one simplifying hypotheses:

$\mathcal{H}$ **2** There is an isomorphism between colors and cover elements.

Due to $\mathcal{H}_2$ it follows that at the symbolic level a bitmap can be represented by a set of terms of the form $cover(\overline{x}, c)$ where $\overline{x}$ denotes a position in the bitmap (in general it denotes a region) and c denotes a color (representing the cover) of $\overline{x}$.

Note that $\mathcal{H}_2$ is a restrictive simplification since in practice it is known that due to noise (e.g. weather conditions) or even to limitations on the process of constructing the image, one same color may be assigned by the satellite to two different geographical coordinates with different covers.

$$\forall \overline{x}, c_1, c_2 \;\; cover(\overline{x}, c_1) \wedge cover(\overline{x}, c_2) \Rightarrow c_1 = c_2.$$

Let Fig. 2 be a ground truth $GRND$ for some $LAND$ with symbolic representation as follows[2]:

$$\begin{array}{llll} cover(1, blu). & cover(3, yel). & cover(5, red). & cover(7, blu). \\ cover(2, blu). & cover(4, yel). & cover(6, red). & cover(8, blu). \end{array}$$

For the cover $GRND$ above we devise[3] two different ways of describing it[4], namely the set IR_1:

$$\begin{array}{ll} cover(x, red) & \leftarrow cover(x-1, yel), cover(x-2, yel) \\ cover(x, red) & \leftarrow cover(x-2, yel), cover(x-3, yel) \\ cover(x, yel) & \leftarrow cover(x-1, blu), cover(x-2, blu) \\ cover(x, yel) & \leftarrow cover(x-2, blu), cover(x-3, blu) \\ cover(x, blu) & \leftarrow cover(x-1, red), cover(x-2, red) \\ cover(x, blu) & \leftarrow cover(x-2, red), cover(x-3, red) \end{array}$$

and the set IR_2:

$$cover(x, C) \;\; \leftarrow cover(x-1, C), \neg cover(x-2, C) \tag{2}$$

$$cover(x, C) \;\; \leftarrow cover(x+1, C), \neg cover(x+2, C) \tag{3}$$

and we have $IR_1(GRND) = GRND$ and $IR_2(GRND) = GRND$, i.e. IR_1 and IR_2 are perfect.

[2]blu, yel, red stand for obvious abbreviations of color names.

[3]The reason why we present the following representations is that both they seem to provide a good description of the pattern in figure. The exact rules are not important – different experts use different rules.

[4]We assume here pixels are numbered in increasing order from left to right.

Figure 3: $img : LAND \rightarrow COLORS$

3.1 Identifying an inconsistency

For illustrative purposes we will adopted here the set IR_2. Let the image received from the satellite be the one shown in Fig. 3 and described by the mapping:

$$\begin{array}{llll} cover(1, blu). & cover(3, yel). & cover(5, yel). & cover(7, blu). \\ cover(2, blu). & cover(4, yel). & cover(6, red). & cover(8, blu). \end{array}$$

Note there is an error at position $\overline{x} = 5$ and $IR_2(cover) \neq cover$. If we use the set IR_2 to interpret *cover* it is easy to find out that the set of consequences of IR_2 given *cover* (i.e. $IR_2(cover)$) contains (among others) the following: $cover(5, red)$, due to the rule instance $cover(5, red) \leftarrow cover(6, red), \neg cover(7, red)$. Similarly $cover(7, red)$ can be derived due to rule (3) in IR_2. In this case, we have that

$$\{cover(5, red), cover(7, red), cover(5, yel), cover(7, blu)\} \subseteq IR_2(cover)$$

and $IR_2(cover)$ is inconsistent (it assigns two different colors to the same position, at positions $\overline{x}_1 = 5$ and $\overline{x}_2 = 7$). In this case, and because IR_2 is perfect we know that the reason for the inconsistency of $IR_2(cover)$ is that *cover* is wrong.

Seeking for an alternative interpretation In the presence of inconsistency the expert has to decide on which colors to assign to $\overline{x}_1 = 5$ and $\overline{x}_2 = 7$.

Alternative Scenario $HMAP_1$ Let us consider we adopt to accept as a good cover that indeed $cover(7, red)$ is true and $cover(7, blu)$ is wrong, i.e. we want to test whether the hypothetical scenario $HMAP_1 = cover\text{-}\{cover(7,blu)\} \cup \{cover(7, red)\}$ is consistent. It can be shown that $\{cover(9, blu), cover(9,yel), \ldots\} \subseteq IR_2(HMAP_1)$ i.e. when we remove the inconsistency of the cover in position $\overline{x} = 7$, an inconsistency arises in position $\overline{x} = 9$.

Alternative Scenario $HMAP_2$ A different scenario can be built which corresponds to adopt for position $\overline{x} = 5$ the cover $cover(5, red)$, i.e. we construct now the possible alternative interpretation scenario $HMAP_2 = cover\text{-}\ \{cover(5,yel)\} \cup \{cover(5,red)\}$ which is consistent because $IR_2(HMAP_2) = HMAP_2 = GRND$, which is the covering we were seeking for.

The reason why it is possible to identify the source of inconsistency in this case, is because IR_2 is known to be perfect. We consider next the case where IR is no longer perfect.

3.2 Defeasible scenarios

We consider now that the bitmap received from the satellite is free from noise, i.e. $GRND = cover$. $IR_2(GRND) \neq GRND$ i.e. the expert IR_2 is no longer perfect, and $IR_2(cover)$ is known to be inconsistent. IR_2 no longer expresses the pattern exhibited by the ground truth, and must be understood now as expressing something slightly different from that in the previous case. We must interpret now rule (3) in IR_2 as:

$$''ALMOST\ \ \forall x''\ \ cover(x, C) \leftarrow cover(x+1, C), \neg cover(x+2, C). \tag{4}$$

A rule of the form (4) provides to be a useful rule, in the sense it is a "good approximation" for the map *cover*. Such a rule is called a *defeasible rule* and its meaning is that it must be applied to every $\overline{x}$ "as long as possible". The only way for $IR(cover)$ to be consistent and still complete is to define rules IR for every $\overline{x}$ in $LAND$ which is in general an impossible task. It can be shown that although $IR_2(cover)$ is inconsistent there is however a subset $IR_3 \subseteq IR_2$ such that $IR_3(cover)$ is consistent, namely[5]: $IR_3 = IR_2 - \{cover(5, red) \leftarrow cover(6, red), \neg cover(7, red)\}$. In this case the consistency in position $\overline{x} = 5$ denotes the position to which the defeasible rule cannot be applied, i.e. $\overline{x} = 5$ is an exception to the general rule (4).

4 Conclusions and Future Work

According to the definition of the image interpretation problem a fully automatic classification algorithm providing reliable and accurate results seems not devisable.

Much work has to be done to extend this approach to a real application, such as (among others) exploration of a high level language (near to the expert), possibly based on concepts as well as the attributes defining the concepts and exploring efficient operational semantics implementing the logic–based declarative semantics. A window–based interactive implementation is being developed.

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[5] recall that IR_2 stands for all the ground instances

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