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Lifelog Data Model and Management: Study on Research Challenges

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Abstract: Utilizing a computer to manage an enormous amount of information like lifelogs needs concrete digitized data models on information sources and their connections. For lifelogging, we need to model one's life in a way that a computer can translate and manage information where many research efforts are still needed to close the gap between real life models and computerized data models. This work studies a fundamental lifelog data modeling method from a digitized information perspective that translates real life events into a composition of digitized and timestamped data streams. It should be noted that a variety of events occurred in one's real life can't be fully captured by limited numbers and types of sensors. It is also impractical to ask a user to manually tag entire events and their minute detail relations. Thus we aim to develop the lifelog management system architecture and service structures for people to facilitate mapping a sequence of sensor streams with real life activities. Technically we focus on time series data modeling and management as the first step toward lifelog data fusion and complex event detection.

Keywords: Event, Information Management, Lifelog, Lifelog Data Model, Real Life Logging.

I. Introduction

A data logging activity recording and tracing one's real life events is called a personal lifelogging. Its application domains include but are not limited to personal/enterprise information management, health-care system and surveillance for the public or for the military. Recent digitized and developed technologies have dramatically changed the way we store information about ourselves. Now lifelogging activities are broadly linked to our daily lives seamlessly and transparently processing our emails, photographs, geo-spatial locations and health records archiving them back to the cloud storage.

However, objective data that has been collected using a variety of sensors gives different subjective feelings to a user by her experiences with that event. This gap between objective

data and subjective feelings is filled up with a myriad of relations that have been built upon by the time a user is exposed to the data, which can be thus evolving with time. Lifelog research is an effort to analyze such real lifelogs to create informative and digitized stories of a person's life that challenges issues in handling disparate media types and various complex technologies for the analysis.

The concept of lifelogging was first proposed early in 1945 by Vannevar Bush [4] and has been quoted in many related works [4, 6, 7, 18, 5, 1, 11]. However its technical data modeling methods or practices have not been well established up to now. In this aspect, Sellen et. al [20] have well summarized issues in which they argued that rather than trying to capture everything, lifelog system design should focus on the psychological basis of human memory to reliably organize and search an infinite digital archive. Technical challenges are then the indexing of heterogeneous media including image, audio, video and human knowledge on their syntactic and ontological meaning expansion. These issues also clearly distinguish lifelog data management from legacy data archiving activities in many aspects.

The following sections address and introduce our approaches to achieve above goals. Section II discusses research challenges of life logs with case studies. Section III introduces a primary raw sensor data preprocessing method converting them into time series streams. Section IV, V and VI detail the E-model architecture that we developed to merge streams for deep and explorative analysis. Promising case studies are reported in Section VII that by using E-model's new and intuitive lifelog recalling services they can be developed without much burden. Finally, Section VIII concludes this paper with the summary of our works.

II. Challenges in Lifelog Analysis

Lifelog inherently involves many heterogeneous data objects in which many data object types and structures are not predetermined when setting up the initial data back-end system.

Its collection gets more complex as more archives and their various analysis results are added on and, for instance, in the query composition for information retrieval. However blind training methods to automatically structure relations [17, 5] between such complex data objects often lack the context of events without which recognized events do not make sense for real-life cases. Instead we think a comprehensive back-end system that facilitates a user or a system to store complex data and to navigate through complex network is more necessary to find clues for information retrieval based on the generalized understanding on events of interests. To make problems and research goals concrete, let us review a number of representative scenarios that frequently happen in lifelog research works [14] and set up our research goals.

A. Complex Data Analysis Case

Let us start with a relatively simple personal lifelogging case in which a person captures her daily activities using her smart phone and neck-held camera or Google Glass like body-mounted sensor device by which she tracks her locations, takes photos and movies, and exchanges emails and SNS messages with others. We assume that all such activities are fairly well time-stamped and uploaded to the cloud server. While the given lifelogging environment looks simple, actual lifelog data often needs very powerful data analysis techniques to retrieve events of user's interests.

For instance in image processing, many photos are taken under various circumstances where lighting conditions and/or motion stability varies significantly by cases. Considering the fact that most image processing algorithms are affected by such environmental conditions, no single algorithm can act on all cases. Even an object detecting algorithm, which is well-trained to detect one or more numbers of event types, often needs a different run-time configuration per environmental changes. It also may need prior works to balance and control the quality of images to keep the algorithm performance high and reliable. Therefore we often apply multiple algorithms to detect similar events from data. Although their outputs might be disparate in terms of data structures or in values, they semantically indicate very correlated events. What we need is then a mechanism to blend and assimilate outputs to draw semantically matching tags to merge event analysis results. In fact, this image processing case is not limited to image types but often occurs in most lifelog media types and their data analysis technologies.

B. Inherited Data Analysis Case

In addition to the image data case shown above, research works on diverse types of lifelog data result in many heterogeneous data where the way to merge and process could be very complex. For example in geo-spatial data, original satellite GPS data can be further analyzed to deduce person's moving direction, speed and paths. Moreover moving speed can be semantically categorized to indicate user's activity status such as whether she was standing, walking, running or riding a vehicle. Reversed geo-coded street addresses can also be tagged by a user as, for instance, her home address, work address or the restaurant where she had a dinner with a number of friends.

All above data are stemmed from, or partially related with, original GPS data although data structures (also called schema) of descendant data objects are all different in the view of database object management. Its back-end should take this into account or else data silos would quickly be filled up with overly diverse data objects in different structures which would increase the complexity in managing the data objects. Also this issue affects almost all aspects of lifelogs ranging from data logging, analyzing, and proving a service back to a user. Though this problem has been a big challenging issue in lifelog research fields, it has mostly been handled using proprietary storage solutions without addressing a generalized event model for lifelogs.

C. Federated Data Grouping Case

The above problem becomes more complex when merging multiple federated personal lifelogs to create the group of lifelogs. Each one may have used different types of sensors and analyzing their interactions would need significant efforts even just to bring them onto the table for comparison. In addition, ownerships of events, complex structural analysis on social relations or tracking physical events shared by members are all similar challenging topics to the back-end database system.

D. Research Goals

From the above observation, we can deduce a number of database design criteria to model real life events. Firstly a structured data model works well for sensor stream data, which are mostly structured and well time-sampled whether in tabular format or in tree format, due to its efficiency in pre-determined structured data parsing and the benefits from the established legacy database system. Secondly data assimilation for expanding the search over to other lifelogs or other types of similar results of one's own logs needs a graph-type database back-end that supports a variety of value examination functions on complex relations for navigation.

III. Time Series Modeling: Converting Sensor Stream to Time Series Data

Data modeling is finding a pattern from the data stream that best describes essential properties of data and distinguishes it from other models. In this aspect lifelog data streams have one distinct property which is that they are a collection of events occurred in our life time. Thus recording its timestamp means that they are historical record while its other entities and their relational structures are disparate by the nature of lifelogs, which might be text, a record or a hierarchical graph-type instance. This can be generalized as a sensor stream in diverse data structures with a time record, i.e. a time series heterogeneous data. To be more concrete, let us first define the generalized time series data structure.

A. Time Series Data Model

Definition 1 A time series data, s_t , is a digitized instance of changes in its source stream, which can be expressed as a tuple of entities:

$$s_t = [t, D], \quad (1)$$

where s is a sensor, t is real-world time and D is the instance of associated entities s_t (ex. GPS information, image Exif data or file data). The data structure of D could be a simple vector, an array (whether in hierarchical), or anything else variable by associated sensors and a system that extracts the raw data from the sensor.

In this era of big data, most back-end systems work as an archive engine to put all data into the database for the detailed or future analysis. Let us start with a use case where we use RDBMS as a back-end. Then the structure of D should be a 1-dimensional unordered entity, which makes the structure of s_t as:

$$s_t = [t, d_1, d_2, \dots, d_n], \quad (2)$$

where d_i is a column instance of table s , which is the collection s_t in a tabular form. Assuming that we have M sensors, then we need to manage M relational tables where each table must have a timestamp column of which the name of a timestamp column might be unified or priori known for interpretation.

One distinct feature of this time series design is that it facilitates the software design for building up the base class to process heterogenous sensor data. One base class may unify common procedures related with streaming data in-and-out procedures. For instance, when we need to handle a number of different time-stamped data like GPS records or photos, its time records and associated data (ex. Exif information of image, geo-spatial locations in GPS records) should each be extracted with different algorithms. Although the data extracted using such tools might be different in terms of structure, the common feature is that by applying stream data we get a timestamped output object. This procedure thus becomes a functional process that reads sensor data to output a timestamp data stream.

$$f(s) = [t, D]. \quad (3)$$

The base class, f , may unify the above process so that whenever we need to handle a new data type, additional inherited classes can be composed with existing sensor classes without huddles. Thus rather than having heterogenous functions for each sensor type like f, g, \dots, z , they can be inherited embedding the common properties like f_1, f_2, \dots, f_M . Also by putting some external program invoking procedures into f , the analytic power of the f can be unlimited and its code can be independent to the types of media. Note that this function is a sensor stream pre-processor to archive the data, not for filtering or windowing the temporal data.

The above process also facilitates the information retrieval by temporal range selection. An example SQL statement that retrieves unions of all tables is shown in Figure 1. The result retrieved by this query will show the distribution of each sensor stream on which we may apply a sort of clustering algorithm to classify them by their density, probability or by the rule of some activity patterns.

This also shows well the limitation of structured data analysis that a query statement will get more complex as more sensor types are added. In a structured query, a data value evaluation must conform strictly to its pre-defined data structure. Also navigating related, whether in spatio-temporal or

semantically, data streams are significantly inefficient. Writing such a query is also complex and often impractical because whenever we need to handle a new data stream type, entire codes need to be modified or updated. This adds a big burden in information management and thus also in querying and walking over related information needs some different data structure.

```
(
  SELECT
    eTimeStamp,
    "sensor_1" AS sensor_name
  FROM sensor_table_1
  WHERE eTimeStamp BETWEEN d1 AND d2
)
UNION
...
(
  SELECT
    eTimeStamp,
    "sensor_M" AS sensor_name
  FROM sensor_table_M
  WHERE eTimeStamp BETWEEN d1 AND d2
)
ORDER BY eTimeStamp
```

Figure. 1: Time series query within the selected time interval.

IV. Lifelog Data Model: E-model

For the application like lifelog, which needs a very abstract and generalized data structure to accommodate and manage heterogenous data streams coming from disparate data sources, a graph data model fits by theory with its rich supports for object inheritance, abstraction (or abstract nodes) and multiple relations (or labeled edges), which feasibly represents complex information networks. However putting all data into such a network-type graph is not practical seeing how it would cause a graph to be too big to manage and query.

Thus we renovated E-model [12] for lifelogging, in which various data models can co-exist in rich relations. We use it as the table top for on-demand analysis to put instances of different data models at one place for in-depth analysis. One idea of E-model is to allow the insertion of new data instances in their own structured form while the access to those instances is also limited to go through its original query mechanism. However at the moment of query, data instances of interests (ex. a portion selected using the query in Figure 1) are translated into the E-model graph on-line for graph search. To achieve the above goal, E-model is designed as follows.

A. E-model Data Structure

The conceptual E-model structure is depicted in Figure 2 using the ORM method [10]. ORM provides a more efficient graphical model description method than the set representation, which needs additional descriptions of the role and constraints of objects. ORM simplifies the design process by using natural language information analysis (NIAM) [16] as well as intuitive diagrams that can be populated with instances. This is done by examining the information in terms of simple or elementary facts like objects and roles to provide a conceptual approach to modeling. We do not get into its details on ORM but will explain features related with E-model.

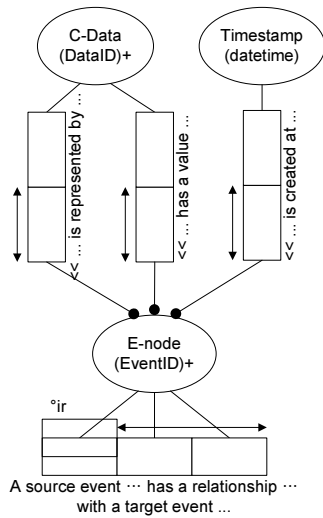


Figure 2: The E-model triplet structure.

Interested readers are referred to [9, 3] for its first formalization in object-role modeling and [10] for the complete list of graphical notations.

In Figure 2, there exist three fact types (e-node type, c-data type for names and values, and the timestamp type) and four predicates (Three predicates to connect an e-node to its entities and the relation predicate for connected between e-nodes). Entity types are depicted as named ellipses. Reference modes in parentheses under the name are abbreviations for the explicit portrayal of reference types. Predicates that explain the relation between two entity types are shown as named sequences of one or more role (rectangle) boxes. An n -ary predicate has n role boxes. For instance, the timestamp of an e-node has the binary predicate with two role boxes. The relation predicate, which needs three e-nodes, has three role boxes. This represents a graph connecting a source e-node to a target event and its connecting edge is again represented using an e-node.

A mandatory role for an object type is explicitly shown by means of a circled dot where the role connects with its object type. In the E-model, the three roles of an e-node (name, value, and timestamp) are mandatory and must exist to define an e-node. A bar across a role is a uniqueness constraint that is used to assert the fact that entries in one or more roles occur there once at most. A bar across n roles of a fact type ($n > 0$) indicates that each corresponding n -tuple in the associated fact table is unique (no duplicates are allowed for that column combination). Arrow tips at the ends of the bar are necessary if the roles are noncontiguous (otherwise arrow tips are optional). As a result, in the E-node, one e-node can have only one set of a name, value, and timestamp.

Definition 2 The e-node is a three-tuple object in which both a name and a value are referred from the c-data set.

$$e = \{d_s, d_v, t\}, \quad (4)$$

where d_s represents a name c-data object, d_v is a value c-data object and t is a timestamp with the following properties:

EN-1 An e-node is a connection identity for a set of a name and a value. For an instance, if one node in a graph

means "Age" and its value is "32", then the ID of this node is an e-node.

EN-2 The transaction time log (timestamp) is attached to record its creation time.

A c-data is devised to be independent to disparate raw data types. Using c-data objects for both name and value significantly changes the way of handling data objects in the information system. This unique architecture is devised based on the observation that in complex data models, names are also data object to query and search. However, most data models treat names as metadata and thus, process them separately. Consequently, the query mechanism of these models depends on their proprietary storage architecture. However, in information retrieval for unstructured data objects like texts, the name of data objects can be the target of a query. For instance, a user may want to query all data objects registered today and labeled as "face." This illustrates that in an unstructured data model, a name and a value are both objects to search. Thus, the E-model uses the same data object type and the identical storage for both name and value objects.

The relations between e-nodes at the bottom of Figure 2 shows the way e-nodes are related with each other. They are represented as the adjacency list of three nodes in which the relation object is located in the center. All three objects in the relation list are referred to e-nodes in which the type of a center e-node is limited to relation e-nodes. Thus an instance of the e-node relation is a triple set:

$$r_x = \{e_s, e_r, e_t\}, \quad (5)$$

where e_s is a source e-node, e_t is a target e-node and e_r is a relation e-node. A number of distinctions we made compared to legacy triple stores, object-oriented model [8, 19] or recent NoSQL back-ends [21] are:

- EM-1 The use of c-data (composite data type) objects for both the name (or called the key) and the value of data, which is devised based on the observation that when writing a query, data names are often objects to find to handle complex data structures.
- EM-2 It is also useful in supporting an imprecise human query not only on data values but also on data names (or keys) and in addition this structure keeps the c-data as a unified data storage type to manage all data values whether for names or values.
- EM-3 By the system design, it allows a significantly fast blind search on both keys and values using only a part of data which is often a critical system performance measurer in the search engine for boosting up the speed of user's initial blind (i.e. unstructured) query.

B. E-model Schema

To support various data structures, E-model introduces the concept of schema as shown in Figure 3. One distinct feature is that all schema objects are again stored as e-nodes and their graph where we do not need an additional storage and mechanism to manage schema objects. E-model schema objects are composed of fundamental elements required to model application domain data.

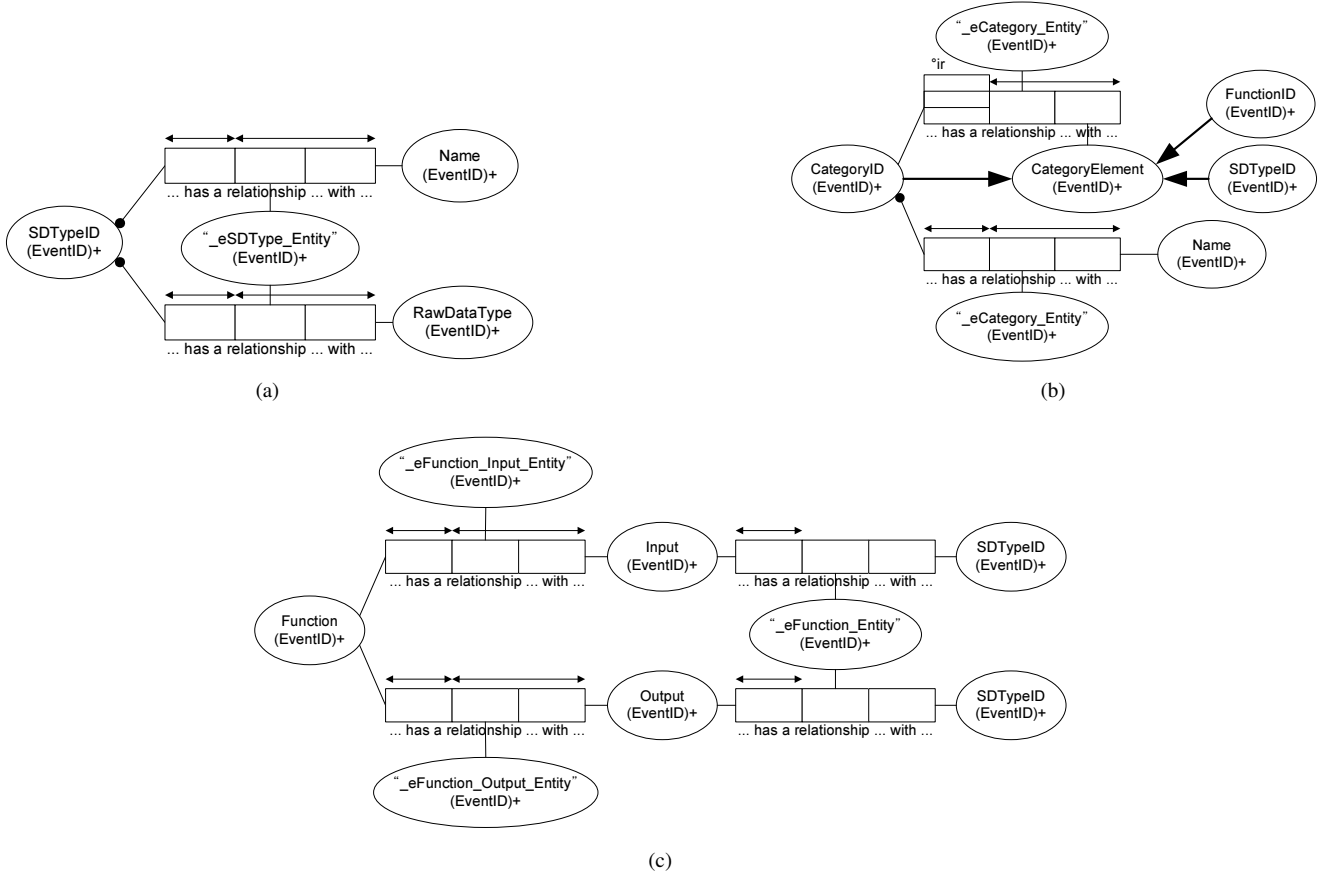


Figure. 3: E-model schema: (a) E-model SD type schema; (b) E-model function schema; and (c) E-model category schema.

1) *e-SDTypes*

In E-model the e-node is an ordered 3-tuple object composed of name, value, and timestamp where the timestamp of an e-node is the transaction time that will be logged when an e-node is registered. Therefore to define the structure of an e-node, its name and raw value data type constitute e-node elements for specification. In this view, the type definition of an e-node, called e-SD type, e_{sd} is a set of two predicates: one e-node $\Phi_{\delta}(e_{sd})$ stores its name and the other e-node $\Phi_{\tau}(e_{sd})$ that stores its raw data type.

2) *e-Function*

To define relationships between e-nodes, E-model uses the concept of the function in place of the relation to distinguish directed relations from the source node to the target node and its connection (called an *edge* in a graph) is labeled as a function name. Thus, the E-model function or e-function, e_f , consists of a domain (source) e-sdtype X and a codomain (target) e-SD type Y with constraints on $x \xrightarrow{e_f} f(x)$, where $x \in X$ and $f(x) \in Y$ and both are e-sdypes.

3) *e-Category*

Merging both e_{sd} and e_f creates a collection of data objects, which is called a category (or class) in other data models. Directed and labeled e-functions allow the data structure to be free enough to model legacy data models and recent diverse data structures. To be more specific, a category of the

data model is (1) a collection of objects, (2) a collection of functions between objects, and (3) child category objects to support inheritance. E-model supports a similar concept with which earlier mentioned E-model schema objects are associated. An e-category, e_c , is a grouping schema object that constitutes a set of structured data objects. An E-model category consists of three elements: (1) e_{sd} as its fundamental data objects, (2) e_f to specify directed relationships between data objects, and (3) child e_c sets for inheritance. An instance of the e_c schema object is called an e-group node. Its child e-nodes have structured relations with an e-group node.

The network composed of e-group nodes strictly follows the temporal order of event occurrence which forces the network of e-groups to form a relational directed acyclic graph (RDAG). RDAG's theoretical properties, search constraints, ordering mechanism and characteristics are introduced in detail at [12].

V. Data Translation

Data translation in E-model is the process of importing instances of other data model (For example like Figure 1) into the E-model database for complex data analysis and exploration over the graph and time. This translation process in between other data models and E-model is mostly very natural and can be formally defined as an algorithm for programming. This section shows an example of working with relational data models and will also indicate how to extend the method for other data models.

A. Understanding E-Model and Relationships with Other Data Models

Translation process in brief for a table structured data is like matching one cell from a table to one e-node in E-model where the identity of one row is represented with an e-group node where the connection between an e-group and its e-nodes is named “relational_row” to specify their original structured relation. It should be noted that e-group nodes should be unique and thus have their own identity value (like UUID or integer-type UUID which we employed) to distinguish its set from others. However e-nodes can be freely shared between e-group nodes. They naturally build up the connected network by values. If the name of foreign keys are the same over two tables, then for E-model natural joins (i.e. Join tables by the same column name) are not even necessary since they are using physically the same e-nodes.

Algorithm 1: Relational database table importing algorithm

Data: Database name D and table name T .
Data: Columns C of T and rows R of T .
Data: Category e-node e_c , its e-sdtype e_{sd} and its e-function e_f .
Data: E-node name c-data ID c_n and e-node value c-data ID c_v .
Data: E-group node e_g .

```

begin
REM   Create the e-category based on the table metadata.
1      $e_c \leftarrow RegisterECatgory(CONCAT(D, ".", T))$ 
      for  $C_x \in C$  do
REM   Register e-sdtypes for columns.
2      $e_{sd} \leftarrow RegisterESDType(C_x.Name, C_x.RawDataType)$ 
      Add new e-sdtype to e-category.
REM   3      $AddESDTypeToECatgory(e_c, e_{sd})$ 
      Import raw data of each column  $C_x$  in  $T$ .
REM   4      $ImportRawData(D, T, C_x.Name, C_x.RawDataType)$ 
      Register e-nodes.
REM   5      $c_n \leftarrow GetCDataID(C_x.Name, "varchar")$ 
      for  $R_x \in R$  do
REM   6          $c_v \leftarrow GetCDataID(C_x.Value, C_x.RawDataType)$ 
REM   7          $RegisterENode(c_n, c_v)$ 
REM   Register e-node relations.
REM   8      $e_{rr} \leftarrow GetEFunction("_eRelation_Row")$ 
REM   9      $e_{rg} \leftarrow GetEFunction("_eGroup_Node")$ 
      for  $R_x \in R$  do
REM   10         $e_g \leftarrow CreateInstance(e_c)$ 
          for  $C_x \in C$  do
             $RegisterRelation(e_g, e_{rr}, e_{\{C_x, R_x\}})$ 
           $RegisterRelation(e_c, e_{rg}, e_g)$ 
end

```

B. Translating Relational Tables into E-model

Instances populated in relational tables match with e-group nodes that are instances of e-categories. Let us first describe the algorithm for importing relational data objects into E-model. Algorithm 1 assumes that the source data is specified with its associated database and table names. If the source is specified with a *SELECT* statement, then E-model first creates a view of the *SELECT* statement and reads the table metadata to register a matching e-category.

Algorithm 1 has several noteworthy features. Line 1 simplifies the hierarchical inheritance from a database object to an associated table with a concatenated string of database and

table names. It creates a unique e-category that should be distinct within the system by concatenating the database and table name that makes it unique in the relational database. If a distinction between the database and the table is necessary, then a hierarchical inheritance from the database to the table can be feasibly modeled by inserting a child table e-category into the database e-category.

At line 2 in registering e-sdtypes, the set of a name and a raw data type of e-sdtypes should be unique in the E-model. If the foreign key in the relation table has the same field name of both the source and target table, then e-categories after the E-model import will share the same e-sdtype. Thus, it naturally supports a foreign key relation. However, if column names linked in the foreign constraint differ, which SQL allows, two approaches can be applied: (1) Add an additional relation (Ex: *_eRelation.Foreignkey*) between source e-nodes and target e-nodes, or (2) use a semantic tag to assign both column names the same semantic meaning.

Line 3 registers each column name as an e-sdtype, which is the child e-node of a table e-category. Line 4 imports all row data by column. Because all data objects in one column have the same name and same raw data type, column import is much faster than row insertion. When the row count exceeds the column count, this is in general a true statement. Line 5 retrieves c-data objects to register column names. Then it is used in a combination of registered column values to register new e-nodes. It should be noted that at this step duplicated name-value pairs are skipped and only new e-nodes will be registered to let the storage maintain the first-normal form (1NF) that has no repetitive values.

Line 7 is where e-nodes are registered. If we are handling more specific data model like streaming sensor data that includes a pre-defined timestamp field in a table, then we can use that information as a timestamp for a new e-node as a replacement of a transaction time for both e-nodes in Line 7 and their group e-nodes in Line 10. Lines 8 to 10 describe the mechanism to create e-group nodes that behave like the row ID of data objects for each record in the table. Finally, all e-groups are registered as child e-nodes of a table e-category.

VI. Data Query and Graph Operations

In relational databases, the relation between two tables is flat. Their semantic meanings, if they exist, are recorded as metadata as part of the comments in table definition or those relations must be deduced from their column names, whereas in a RDAG, a relation is a distinct e-node object. When it becomes flat (use of only one relation type), then a RDAG behaves like a sequence of first-order relations, which is similar to the relational models depicted in Figure 4.

A. Data Query

For an actual importing example, let us assume that we want to retrieve all three e-node sets $\{e_1, e_4, e_5\}$ having the relation R_1 in between $\{e_1, e_4\}$ and R_4 in between $\{e_4, e_5\}$. Note that the numbers of relational tables in Figure 4 represent the column names in an abstract way that is not permitted in the SQL standard. In a relational database such a query becomes two inner joins as shown in Query 1:

Query 1 *Relational table join example.*

Table 1: E-model query function format.

Format	Return type	Explanation
$Q(e_s)$	$\bigcup_{i=1,\dots,N} \{e_{r_i}, e_{t_i}\}$	Search all $\{e_r, e_t\}$ pair in any relation
$Q(e_t)$	$\bigcup_{i=1,\dots,N} \{e_{s_i}, e_{r_i}\}$	Search all $\{e_s, e_r\}$ pair in any relation
$Q(e_r)$	$\bigcup_{i=1,\dots,N} \{e_{s_i}, e_{t_i}\}$	Search all $\{e_s, e_t\}$ pair in e_r relation
$Q(e_s, e_r)$	$\bigcup_{i=1,\dots,N} e_{t_i}$	Search all target e-nodes from e_s in e_r relation
$Q(e_s, e_t)$	$\bigcup_{i=1,\dots,N} e_{r_i}$	Search all relations between e_s and e_t
$Q(e_r, e_t)$	$\bigcup_{i=1,\dots,N} e_{s_i}$	Search all source e-nodes from e_s in e_r relation
$Q(e_s, e_r, e_t)$	N	Return the count of the specified relation set

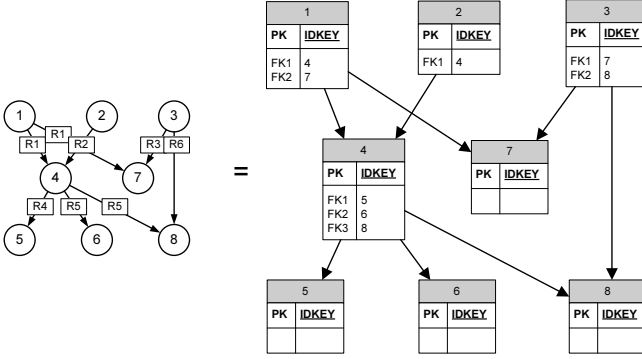


Figure 4: RDAG-to-relational model mapping example.

```

SELECT t1.IDKEY
FROM t1
INNER JOIN t4 ON (t4.IDKEY = t1.4)
INNER JOIN t5 ON (t5.IDKEY = t4.5)

```

Relational joins that appear in Query 1 can be represented more succinctly in E-model. Let us first define the query function of E-model.

Definition 3 An E-model query function, Q , is a search function for e-nodes and it is composed of constraints on source, relation and target e-nodes: $Q(e_s, e_r, e_t)$.

Possible combinations and returning data structures are specified in Table 1. When a Q returns e-node sets, then it can be embedded in other Q forming a sequential query sequence. Query 1 for relational tables can be represented in the Q expression like the following:

$$e_d :=> Q(R_1, Q(e_4, R_4, e_5)), \quad (6)$$

where e_d is a source e-node set to find and R_1 and R_4 are flat when applied to relational tables. Apparently same E-model query functions can work on other data models by changing only R for that data model. Actually, we have developed a bucket of data model importers (RDBMS, JSON and XML) similar to Algorithm 1.

B. Path Query: M-algorithm

To support RDAG path searching, let us formulate an algorithm for finding such related e-nodes as a way to find a path between two e-nodes and through a shared e-node. Figure 5 depicts the flow of queries from A to E for finding relations between two e-nodes. This figure shows a case in which two e-nodes (A and E) do not share the same group node, but they are related by another e-node (C). This query is independent of the associated categories since it looks for the connected and shared e-node that is independent from its associated e-category. In other word, this query is an unstruc-

tured query.

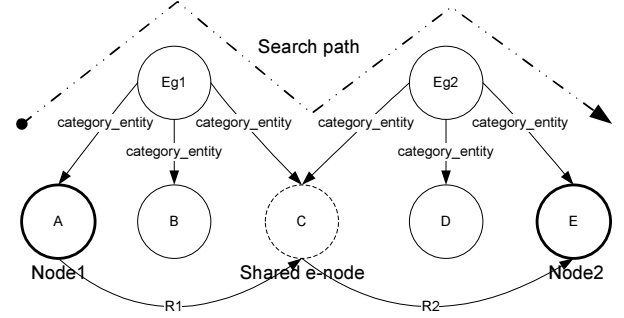


Figure 5: Related information search over group nodes.

From given input data values and types, we first find the seed e-nodes, E_{p_1} and E_{p_2} to search for a path between the two. Then we proceed to find other e-nodes under the same category. If no matches are found in the sibling e-nodes, the search moves up one level to the parent e-group node. Through this bottom-up manner, the search keeps moving upward until it arrives at the super e-node. This algorithm is designated the M -algorithm. Its set representation is formulated at Eq. 7.

$$\begin{aligned}
E_{p_1} &= C(f_e(A)), E_{p_2} = C(f_e(E)), \\
E_c^{p_1} &= S(E_{p_1}), E_c^{p_2} = S(E_{p_2}), \\
f_e(c) &= E_c = E_c^{p_1} \cap E_c^{p_2},
\end{aligned} \quad (7)$$

where f_e is the function to find e-nodes of a given data value (A and E in Figure 5). C is a function to retrieve a category e-node. S is a function to find all entity e-nodes from a given e-group node, and E_c is a result set of e-nodes that $E_c^{p_1}$ and $E_c^{p_2}$ commonly share.

Because a RDAG permits multiple relations between e-nodes, the same e-nodes may be connected in multiple relations. Such multiple relations can be limited to specific ones to reduce the computational load. In this query, even without any knowledge of an e-node symbol or value, a user can query a set of source and target e-nodes using a specific relation. This is a simple and powerful solution when a user is looking for e-nodes in special relations so as to retrieve all related e-nodes.

In addition, all data objects in a RDAG are e-nodes, and they are the composition of c-data objects. The keyword query method is thus equivalent to all RDAG objects without prior knowledge of their relations. This means that a keyword query for all e-categories is very efficient, and once found, the navigation through the connection in a RDAG is straightforward without the need to look for additional metadata. In other words, e-group nodes of a RDAG are instances

of e-category instances, and the M-algorithm is an unstructured query method for structured objects.

Algorithm 2: M-algorithm - Homogenous (RDAG)

Data: Two data and/or name values to find the path between them, I_x and I_y .
Data: Constraints on each value, L_x and L_y .
Result: The path set, P_{xy} , stores all possible routes from $\{e_{p_x} \in E_{p_x}\}$ to $\{e_{p_y} \in E_{p_y}\}$.

```

begin
REM Find the seed e-nodes from a given input data value.
 $E_{p_x} \leftarrow FindNodes(e_d(I_x), L_x)$ 
 $E_{p_y} \leftarrow FindNodes(e_d(I_y), L_y)$ 
REM Retrieve the parent e-group nodes.
 $E_c^{p_x} \leftarrow GetParentNodes(E_{p_x})$ 
 $E_c^{p_y} \leftarrow GetParentNodes(E_{p_y})$ 
REM while  $|E_c^{p_x}| \neq \emptyset$  and  $|E_c^{p_y}| \neq \emptyset$  do
Check the connection between two e-nodes,  $e_{p_x}, e_{p_y}$ .
for  $e_{p_x} \in E_{p_x}$  do
for  $e_{p_y} \in E_{p_y}$  do
REM if  $e_{p_x} = e_{p_y}$  then
Store path.
 $P_{xy} \leftarrow StorePath(e_{p_x}, e_{p_y})$ 
else
 $E_c^{c_x} \leftarrow GetChildNodes(e_{p_x})$ 
 $E_c^{c_y} \leftarrow GetChildNodes(e_{p_y})$ 
REM Find the common e-node that two e-group
nodes share.
 $e_{c_x} = E_c^{c_x} \cap E_c^{c_y}$ 
if  $IsNotNull(e_{c_x})$  then
REM  $P_{xy} \leftarrow StorePath(e_{p_x}, e_{c_x}, e_{p_y})$ 
When it reaches the super e-node, then stop.
 $E_c^{p_x} \leftarrow GetParentNodesExceptSuperNode(e_{p_x})$ 
 $E_c^{p_y} \leftarrow GetParentNodesExceptSuperNode(e_{p_y})$ 
end

```

To search for more than connected data objects, temporal relations and their operators [2] can be naturally applied to queries. Because all e-nodes have a transaction timestamp, temporal relations can be used in searching for e-nodes on the timeline. If a user wants to search for information using a valid time [15], then the query can be extended to find the timestamp-type e-nodes under the same e-group node. This permits a query to be expanded over other e-nodes that have timestamp-type c-data with the same symbol c-data within specified temporal ranges. In addition, semantic expansion using a shared dictionary is feasible because it is limited to finding e-nodes to search for at the first step.

The above ideas are formulated as the M-algorithm. The M-algorithm is a method to find the path between two e-nodes through a shared e-node. We developed the M-algorithm in two versions. Algorithm 2 is for a case that follows a RDAG within associated e-categories and its super e-node. Algorithm 3 allows the search to walk over heterogeneous categories in which sibling e-nodes are associated. Algorithm 3 also permits a search across different super e-nodes, in other words, a search over the distributed network.

Several functions are defined for the M-algorithm. *FindNodes* finds e-nodes based on given reference values of a symbol and/or a data value. Because one e-node is composed of two c-data objects and one transaction timestamp, search constraints can be specified on these three entities. *FindNodes* is based on a Search-by-Value (SBV) algorithm

that according to our E-model system, has superior performance compared to popular storage models. *GetParentNodes* retrieves e-group nodes from a given e-node based on the RDAG network. It returns the first parent e-node and multiple e-nodes because one e-node may be referenced multiple times by different e-group nodes. *GetChildNodes* returns all child e-nodes from a given parent e-group node.

In the case of the heterogeneous M-algorithm, the search pool has no pre-navigation boundaries. Also, when the search moves over different super e-nodes, the temporal constraint in one RDAG does not apply to another RDAG. Hence, in the algorithm, several constraints are applied to searching e-nodes. For instance, T_r limits the time range. When a user wants to find “near” events or previous events only, then T_r can work as the temporal window to limit the e-nodes in the search. If a user want to search over special relations like specific spatio-temporal relations, then such conditions can be modeled as L_r . Both algorithms finish searching when their trace moves up to an associated super e-node.

Algorithm 3: M-algorithm - Heterogenous (RDAG)

Data: Two data and/or name values to find the path between them, I_x and I_y .
Data: Constraints on values, L_x and L_y .
Data: Constraints on relational time ranges, T_r .
Data: Constraints on relations, L_r .
Result: The path set, P_{xy} , stored all possible routes from $\{e_{p_x} \in E_{p_x}\}$ to $\{e_{p_y} \in E_{p_y}\}$.

```

begin
REM Find the seed e-nodes from a given input data value.
 $E_{p_x} \leftarrow FindNodes(I_x, L_x)$ 
 $E_{p_y} \leftarrow FindNodes(I_y, L_y)$ 
REM Retrieve the parent e-group nodes.
 $E_c^{p_x} \leftarrow GetParentNodes(E_{p_x})$ 
 $E_c^{p_y} \leftarrow GetParentNodes(E_{p_y})$ 
REM while  $|E_c^{p_x}| \neq \emptyset$  and  $|E_c^{p_y}| \neq \emptyset$  do
Check the connection between two e-nodes,  $e_{p_x}, e_{p_y}$ .
for  $e_{p_x} \in E_{p_x}$  do
for  $e_{p_y} \in E_{p_y}$  do
REM if  $e_{p_x} = e_{p_y}$  then
Store path.
 $P_{xy} \leftarrow StorePath(e_{p_x}, e_{p_y})$ 
else
 $E_c^{c_x} \leftarrow GetChildNodes(e_{p_x}, t \in T_r)$ 
 $E_c^{c_y} \leftarrow GetChildNodes(e_{p_y}, t \in T_r)$ 
REM Find the common e-node that two e-group
nodes share.
 $e_{c_x} = E_c^{c_x} \cap E_c^{c_y}$ 
if  $CheckConstraints(e_{c_x}, L_r)$  then
REM  $P_{xy} \leftarrow StorePath(e_{p_x}, e_{c_x}, e_{p_y})$ 
Expand the search over sibling e-nodes' parent
e-nodes.
When it reaches the super e-node, then stop.
 $E_c^{p_x} \leftarrow GetParentNodesExceptSuperNode(E_c^{c_x})$ 
 $E_c^{p_y} \leftarrow GetParentNodesExceptSuperNode(E_c^{c_y})$ 
end

```

In addition to above data joining examples, deeper analysis can be done on the E-model graph. For the data translated into E-model, search-by-value, walk over the graph and temporal association like much-have functions for deep data exploration and navigation are naturally supported. Details of this implementation are introduced in [12]. In this work, an earlier E-model prototype and its APIs are completely ren-

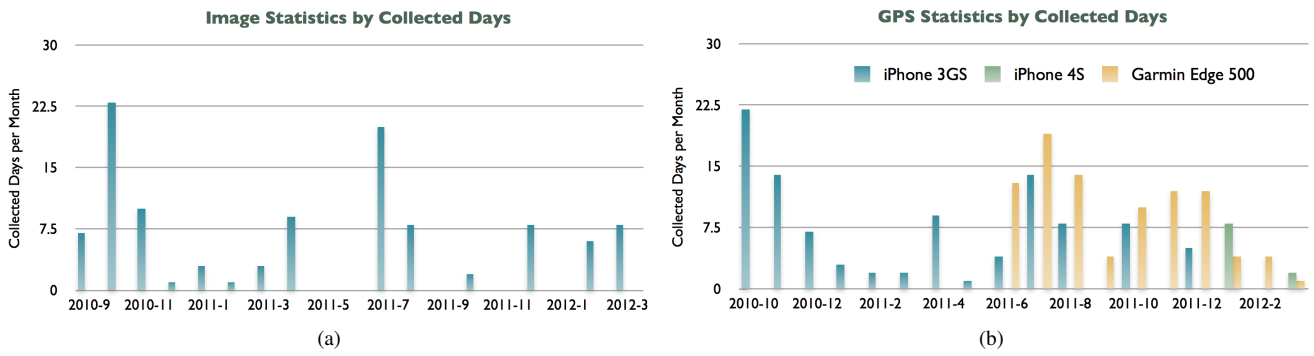


Figure. 6: Lifelog statistics: (a) Image collection status by days per month and (b) GPS collection status by days per month.

ovated to work with time series stream data and now they support server-side APIs to interact with sophisticated user interfaces.

VII. Case Study: Real Life Logging

For the case study to evaluate E-model for real-world application cases, we have selected 109 days of personal life logs collected over 18 months (See the statistics in Figure 6) using a number of sensors including ViconRevue, GoPro, iPhone and Garmin GPS. Most activities are captured during the day time including working hours, weekends and some social events. It is not forcefully captured every day but by time-to-time or when important events happened to record. In other words, our data logging experiment means to record human’s normal daily activities not proprietarily settled for life recording in mind.

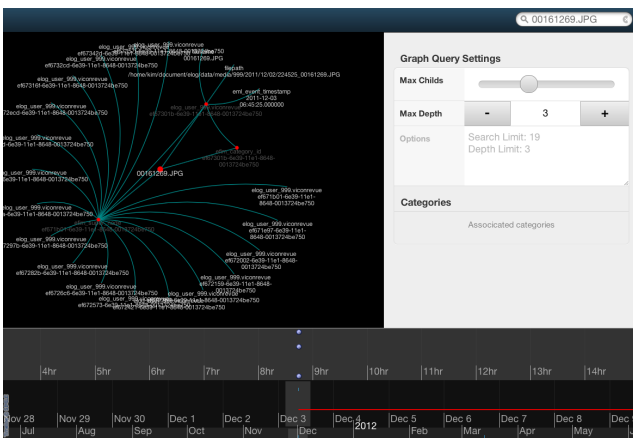


Figure. 7: The E-model graph query interface.

A. Demo: E-model Graph Explorer

Figure 7 shows our current UIs for E-model graph exploration using the M-algorithm (See Algorithm 2 and Algorithm 3). In this demo, it first starts with a text query put on the top-right search box. A user can specify the graph search depth and the number of nodes to search for the first iteration. Each node in a graph is clickable to expand the search over connected nodes. In this procedure, a user is completely free from the constraint of structured data models where a user should know its structure before writing any

queries. In addition the time chart shown at the bottom pane reveals the group of events that happened during the same period. Hence the search can be expanded over not related by data values or other hard-wired relations but occurred at the same moment that a user might be interested to look for to get more accurate insight and understanding on events.

B. Demo: Spatio-temporal Event Viewer

We have expanded E-model APIs to interactively communicate with Web UIs and external data services or sources. One example shown in Figure 8a is to implement the concept over converting heterogeneous data sources into time series streams to view events and their relations over the timeline. This demo shows amalgamation of GPS and photo data streams where GPS points are clustered by the map zoom level. Each GPS cluster is clickable to show a reverse geocoded real street address so that a user can identify the exact location of an event. Selecting a cluster shows all photos at the top-right pane that have been captured at the selected location through the entire time a user has archived. Also the bottom-right pane provides a timeline to see exactly when those photos are taken at the selected place. By using this new and intuitive spatio-temporal photo viewer interface implemented atop E-model, a user can freely check out photos of her interests by time and location.

Making the example more complex, the next case shown in Figure 8b is finding commuting events between the user’s home and work place. From given GPS clusters, a user can select two clusters (*A* for the departing point and *B* for the arriving point as shown in the figure). Then the E-model system automatically calculates all GPS tracks from the history and clusters all locations on-line. The top-right pane shows found continuous GPS tracks and when selected, it shows the photo stream at the bottom-right pane. In this example, a user selected her home and her office location and when selecting one from the timeline, the photo pane shows all photos taken during her commuting hours. An interesting question a system may answer using this interface is “Something happened when I was going to the company but I can’t remember exactly when it was and where it was in between my home and the company.” This complex query can be answered very naturally using E-model.

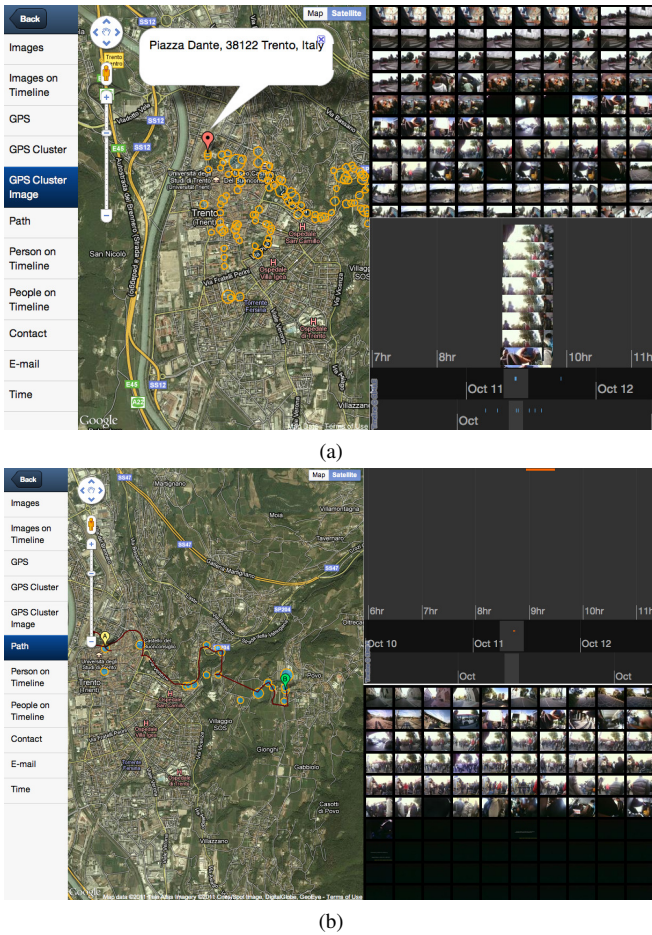


Figure 8: e-Log user interfaces: (a) Spatio-temporal photo viewer and (b) Find GPS tracks (Commuting events in this case) between two places and review images taken then.

C. Demo: Managing Unstructured/Structured Data

Photos taken by imaging devices can be further analyzed using modern computer vision technologies. Figure 9a shows the flow of automatically detected human faces and the name-tagged data over the time. This screenshot shows an example that a user queries people she met for one selected day.

Let us merge this photo stream with the email stream to develop a new innovative email search system. The legacy query interface on the email data, which includes unstructured text data, uses the full-text index on which we perform keyword search queries. In this case study, we convert them into the streaming data in which an email transaction time as its timestamp and put all into the E-model database for data query. By temporally aligning the email stream with the face stream, we could develop a new email UI shown in Figure 9b. This demo shows the screen shot in which we search a dinner event with a keyword “pizza” and then by the found and selected email timestamp it shows people on the right pane on the timeline with which we can identify people we had a pizza together. These new types of interface are easy to develop using the E-model system making its application domain much broader than prior legacy information management systems.

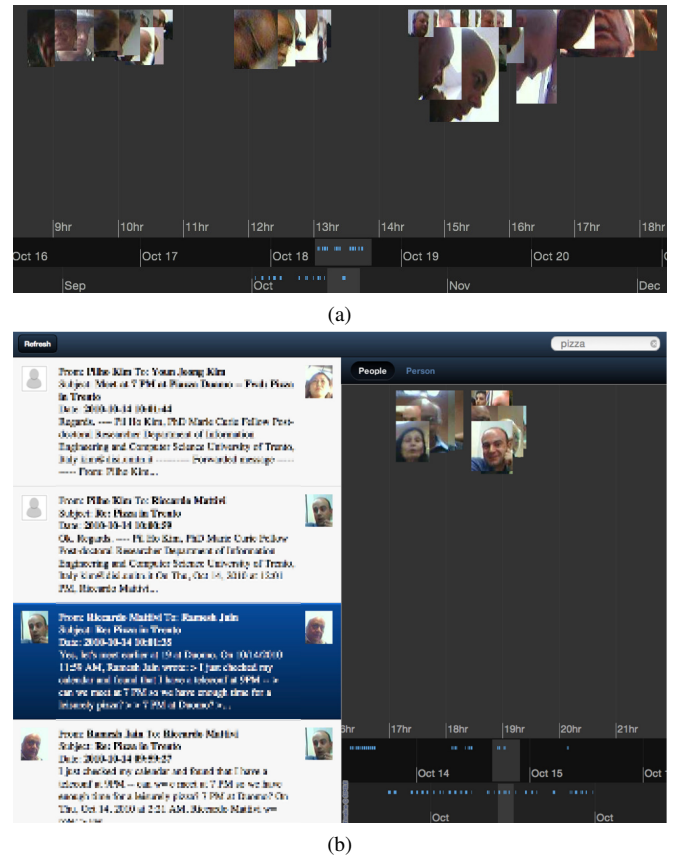


Figure 9: e-Log user interfaces: (a) Tagged face flow example showing people a user met for one day. and (b) Keyword event search case: Email search interface over the timeline.

VIII. Conclusion

This paper extended our previous works ([13] and [14]) in which we addressed the need and our earlier approaches for collaborated lifelog research environment. This paper described the most recent progress a step toward our goal since then. Also E-model, which was first introduced in [12], is much more enhanced to handle big lifelog data in a way that they are first archived into time series streams for archiving and then translated into the E-model graph for big data analysis.

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Fausto Giunchiglia received his MS and PhD in Computer Engineering from University of Genoa, Italy in 1983 and 1987. Dr. Giunchiglia joined University of Genoa, Italy in 1986 as an Adjunct Professor and also has worked for ITC-IRS in Italy, University of Edinburgh in UK and Stanford University in USA. He moved to University of Trento, Italy in 1992 and became a Professor of Faculty of Science in 1999. He is member of the ERC panel for the ERC Advanced Grants (2008-2013). He has been the program or conference chair of IJCAI 2005, Context 2003, AOSE 2002, Coopis 2001, KR&R 2000 and IJCAI (05-07). He has developed very influential works on context, lightweight ontologies, ontology (semantic) matching and also peer-to-peer knowledge management. He has participated in many projects, (Open Knowledge, Knowledge Web, ASTRO, Stamps, etc.) and also has coordinated EUMI and EASTWEB.