Software Design Patterns for Information Visualization

Jeffrey Heer and Maneesh Agrawala

Abstract—Despite a diversity of software architectures supporting information visualization, it is often difficult to identify, evaluate, and re-apply the design solutions implemented within such frameworks. One popular and effective approach for addressing such difficulties is to capture successful solutions in design patterns, abstract descriptions of interacting software components that can be customized to solve design problems within a particular context. Based upon a review of existing frameworks and our own experiences building visualization software, we present a series of design patterns for the domain of information visualization. We discuss the structure, context of use, and interrelations of patterns spanning data representation, graphics, and interaction. By representing design knowledge in a reusable form, these patterns can be used to facilitate software design, implementation, and evaluation, and improve developer education and communication.

Index Terms—Design patterns, information visualization, software engineering, object-oriented programming

1 Introduction

As recognition of the value of visualization has increased and the demand for visual analytics software has risen, visualization researchers have developed numerous software frameworks to meet these needs. By changing the cost structure governing the design and implementation of visualizations, such frameworks carry the potential to lower barriers to entry and increase the space of feasible visualization designs. Still, there is never a single tool or framework that is appropriate for all problems in a given domain. Developers often migrate between tools (*e.g.*, when developing on a new platform) or build their own systems (*e.g.*, to achieve functionality not available elsewhere). In either case, an understanding of the design solutions employed within existing tools could aid the programmer in learning and evaluating other frameworks and furthering their own development efforts. However, inspection of source code and design documents, if available, can prove difficult and tedious. Descriptions in the research literature often place more emphasis on novel features than on recurring design patterns. As a result, it can be difficult to identify, evaluate, and re-apply the design solutions implemented within existing frameworks.

Similar issues permeate any discipline steeped in design. Originally developed by Christopher Alexander and his colleagues in architecture [2], *design patterns* have proven to be a useful means of capturing time-tested design solutions and facilitating their reuse. Patterns aim to explicitly represent design knowledge that is understood implicitly by skilled practitioners.

Perhaps nowhere has the pattern approach been more effective than in software engineering. Gamma et al. [13] describe *software design patterns* as "descriptions of communicating objects and classes that are customized to solve design problems within a particular context." Such patterns document object-oriented software design solutions in a fashion independent of specific programming languages. Patterns typically consist of a name, a purpose, a description of when and why to apply the pattern, structural diagrams, examples of use, and a discussion of interactions with other patterns.

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Schmidt [18] has noted a number of benefits gained from incorporating design patterns into the development process. He found that patterns enabled widespread reuse of software architecture designs, improved communication within and across development teams, facilitated training of new programmers, and helped transcend ways of thinking imposed by individual programming languages. Schmidt also recommends that practitioners focus on developing patterns that are strategic to a domain of interest, while reusing general-purpose patterns (*e.g.*, those of [13]) as much as possible—an approach we now adopt for the design of information visualization software.

Previous research has applied the design pattern approach to visualization problems. Stolte et al. [21] introduce design patterns describing different forms of zooming within multi-scale visualizations. Chen [7] takes a more ambitious approach, suggesting high-level *visualization patterns* addressing general visualization concerns. He lists patterns such as Brushing, Linking, and Encoder, the latter encompassing in a single pattern the visual encoding principles (*e.g.*, use of spatial position, color, size, and shape) advocated by Bertin [4], Cleveland [10], Mackinlay [17], and others.

In contrast, this paper considers patterns at a lower level of abstraction, building upon the approaches of Gamma et al. [13] and Schmidt [18] to focus specifically on software design patterns for information visualization applications. We present a set of twelve design patterns that have proven themselves in existing visualization frameworks, spanning issues of application structure, data handling, graphics, and interaction. The patterns were chosen based upon a review of existing frameworks and our own experiences building prefuse [14], an open source toolkit for building interactive visualizations. As Schmidt warns [18], not everything should be cast as a pattern, even if it is possible to do so. We have attempted to select only those patterns whose recurrence and/or significance warrants their inclusion.

2 Design Patterns

We describe a set of twelve design patterns for information visualization software. Each pattern consists of a name, a summary description (in italics), and a more detailed description describing the context of use, examples, and relations to other patterns. Each pattern is also accompanied by a structural diagram that uses the conventions of Gamma et al. [13] to depict the classes and the relations between them, such as inheritance, reference, and aggregation. Figure 1 provides a legend for interpreting the structural diagrams. The structural diagrams do not specify full-blown implementations; they provide an abstracted view to communicate the essence of the pattern.

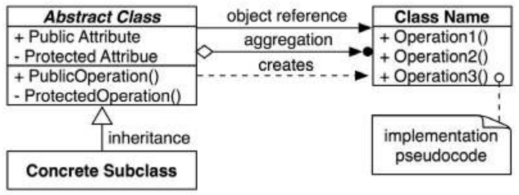


Figure 1. Structural diagram legend. Classes are depicted as boxes, potentially listing attributes and method signatures. Abstract classes are titled using italics. Arrows indicate relationships between classes. These relations include inheritance, denoted by a large empty triangle; object reference, denoted by an unadorned arrow; aggregation, denoted by a diamond base; and creation, denoted by a dotted, labeled arrow. A circle at the arrow endpoint indicates a 1-to-many relation. Notes, depicted as a box with a folded corner, are used to communicate implementation information in pseudocode.

2.1 Reference Model

Separate data and visual models to enable multiple visualizations of a data source, separate visual models from displays to enable multiple views of a visualization, and use modular controllers to handle user input in a flexible and reusable fashion.

Information visualization application development requires balancing issues of data management, visual mappings, computer graphics, and interaction. Determining the right separation of concerns has serious consequences for the complexity, extensibility, and reusability of software architectures. The *Reference Model* pattern provides a general template for structuring visualization applications that separates data models, visual models, views, and interactive controls.

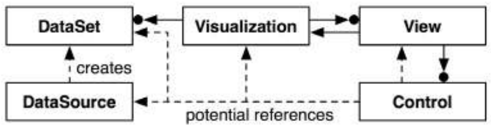


Figure 2. The Reference Model Pattern. A visualization manages visual models for one or more data sets, separating visual attributes (location, size, color, geometry, etc) from the abstract data. One or more views provide a graphical display of the visualization, while control modules process user input and may trigger updates at any level of the system.

The structure of the *Reference Model* pattern is shown in Figure 2. A DataSource component, such as a formatted file reader or a database connectivity interface, loads data sets to be visualized. One or more data sets can then be registered with a visualization. This mechanism allows abstract data to be separated from visual attributes such as location, size, shape, and color, thereby allowing a single abstract data set to be used in multiple visualizations. A common approach is to create *visual items*: lightweight components representing an interactive visual object in the visualization.

The Visualization, View, and Control classes employ the standard *Model–View-Controller* (MVC) pattern [16] of user interface development. A visual model can be shown in one or more views, with user input processed by controls that can affect change at any level of the system. One way of interpreting this pattern is as a tiered version of MVC, with the model divided into separate abstractions for the data and visual properties.

The Reference Model pattern has been widely used and advocated. Both Chi et al's *data state model* [8] and Card et al's *infovis reference model* [6] proscribe the use of this pattern. In their exploration of design choices for architecting visualizations, Tang et al. [22] also discuss the importance of separating data and visual models. Finally, numerous software frameworks adopt this template of application structure, including Advizor [11], Improvise [23], Polaris [20, 21], prefuse [14], and SAS/JMP [7].

The *Reference Model* pattern provides a high-level template for application design whose implementation can be informed by other patterns. The DataSource components may use the *Abstract Factory* or *Factory Method* patterns of [13] to instantiate objects without specifying concrete classes. Update notifications can be passed between objects using the *Observer* (or *Listener*) pattern [13]. For example, Views can listen for update events issued by the Visualization. Control objects represent components in a *Strategy* pattern [13], as each represents a strategy for handling user input that can be added or removed at run-time. Each of the remaining patterns presented in this paper also contribute to the implementation of this model.

2.2 Data Column

Organize relational data into typed data columns, providing flexible data representations and extensible data schemas.

The most common data representation used in visualization is the relational model or "data tables" [6], with a table row representing a single data record (also called a *relation* or *tuple*) and table columns representing individual data fields. The description of a table's column structure, including each column's name and its contained data type, is called a *schema.* Database management systems regularly store relational data in row-major order, as keeping the contents of a relation in a contiguous block helps minimize disk usage when evaluating queries. Information visualization systems, however, primarily manage data sets in main memory and are faced with the design decision of internally grouping data by row or by column.

A row-based approach has the advantage of treating data records as individual objects, enabling easy grouping and sorting of relations. A column-based approach, however, often simplifies data management. Columns can be added and removed more easily, and columns can be shared across tables, facilitating data reuse. Each column can implement its own data management policy to more efficiently store data. When representational flexibility and extensible schemas are needed, the *Data Column* pattern can be applied to implement column-based relational tables.

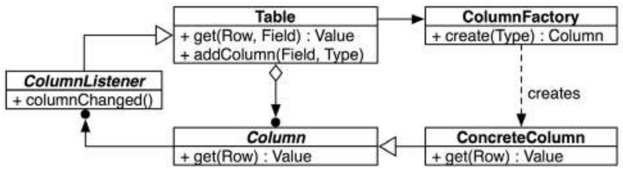


Figure 3. The Data Column Pattern. Relational data tables are implemented as a collection of column objects. Data columns encapsulate data representation and can be shared among tables, propagating value updates using the Observer pattern [13]. A factory pattern can be used to facilitate column creation.

The structure of the *Data Column* pattern is shown in Figure 3. Tables are represented as an aggregation of column objects. Column objects can be shared across multiple tables, with update notifications provided to each enclosing table. Data representation strategies can vary by column (an instance of the *Strategy* pattern [13]). For example, integers might be stored in an array, boolean values in a compact bit vector, while sparse data representations could be applied in situations of low data density. Furthermore, table schemas can be modified with little overhead, by simply adding or removing column instances from the table.

Tables can handle column access in multiple ways. Data columns can be referenced by number (using an array look-up) or by name (using an associative map). It is also useful to include a row manager, which tracks the currently occupied rows and, if needed, maintains a map between table row numbers and column row numbers. These numbers may differ if filtered tables are supported, a possibility discussed later (§2.3). A row manager can also be used to track added and deleted rows, supporting dynamic tables by reusing memory occupied by a deleted row.

The *Data Column* pattern has been applied in many visualization frameworks, including Advizor [11], the InfoVis Toolkit [12], prefuse [14], and SAS/JMP [7]. However, row-based frameworks such as Polaris [20] are more amenable to tasks such as sorting and grouping table rows. Creating sorted *indices* of column values relieves some of these issues. An additional solution is to apply the *Proxy Tuple* pattern (§2.5), creating an object-oriented interface to individual table rows. Finally, the *Abstract Factory* or *Factory Method* patterns [13] can be applied to instantiate polymorphic data columns based on criteria such as data type and sparsity.

2.3 Cascaded Table

Allow relational data tables to inherit data from parent tables, efficiently supporting derived tables.

In many cases, it is necessary to extend the contents of a table without modifying it. A motivating example is the creation of visual abstractions, which add visual attributes such as location, color, size, and shape to an existing data model. In accordance with the *Reference Model* pattern, a separation between the visual data and the original data should be maintained. Another example is the creation of small multiples displays, which might vary a single visual property such as color across each display. It is desirable to reuse the remaining properties across each of the display models and coordinate updates to these properties. The *Cascaded Table* pattern provides a solution to this problem for relational data by extending an existing table without modifying it.

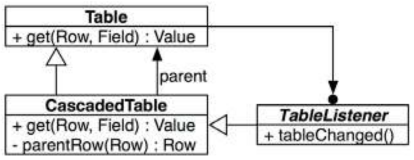


Figure 4. The Cascaded Table Pattern. A cascaded table inherits values from a parent table instance. The cascaded table may manage its own set of data columns, potentially shadowing columns in the parent. Column references not found in the child table are resolved against the parent table.

The structure of the *Cascaded Table* pattern is shown in Figure 4. A CascadedTable subclasses Table and also maintains a reference to a parent table. If a requested column is not found in the child table, the request is forwarded to the parent. CascadedTables may contain data columns that shadow columns in the parent table. For example, adding a new column with the same name as a column in the parent will override access to the parent's column. Update notifications are relayed from parent tables to child tables, achieving coordination between parent and child. By extending a parent table with additional data, the *Cascaded Table* pattern is an example of Gamma et al's *Decorator* pattern [13].

Proper use of the *Cascaded Table* pattern requires a row manager that maps between the rows of the child table and its parent table. Such management is especially useful when cascaded tables provide filtered views of the parent. For example, clients might specify a filter predicate to limit the rows accessible from the cascaded table (see the *Expression* pattern in §2.6).

The *Cascaded Table* pattern is used extensively in the prefuse visualization toolkit [14] to form visual abstractions, decorating a data set with visual properties. The resulting cascaded table provides easy access to both visual properties and the underlying data through a unified interface. Cascaded tables are also applied to create derived visual tables that override only a subset of visual properties, enabling reuse both within a display (*e.g.*, adding labels onto shapes) or across displays (*e.g.*, the small multiples example discussed earlier).

2.4 Relational Graph

Use relational data tables to represent network structures, facilitating data reuse and efficient data processing.

Second to relational data tables, network structures such as graphs and trees are amongst the most common data structures used in information visualization. These structures are typically implemented in an object-oriented fashion, with node objects storing adjacency lists of connected node and edge objects. However, in visualization frameworks this representation creates an incongruity between network and table data structures and sacrifices benefits of relational data management (*e.g.*, optimized query processing). The *Relational Graph* pattern addresses the issue by implementing network structures using relational data tables. Relational graph structures allow the machinery of relational tables to be used on network data and enable a level of data reuse unsupported by the typical object-oriented model.

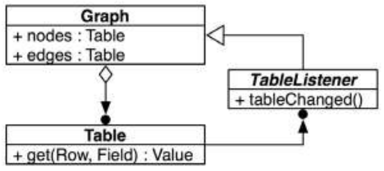


Figure 5. The Relational Graph Pattern. Network structures are implemented using relational data tables to represent node and edge data. Edge tables maintain foreign keys which reference incident nodes.

The structure of the *Relational Graph* pattern is shown in Figure 5. A network structure such as a graph or tree can be represented using a set of tables. Each table stores the various data attributes of nodes and edges in the network. The edge table additionally maintains columns referencing source and target nodes, storing identifiers (called foreign keys) that map into a node table. This model mirrors the standard format of linked structures within relational database management systems. Tree structures can enforce topological constraints on the edge table, allowing only parent/child relationships. Multiple node tables may be used to model partite graphs or nodes with varying data schemas. In these cases, separate edge tables can be used to record edges between each pair of node tables.

There are numerous advantages to the relational graph approach. First, it helps unify data representation issues in multi-purpose visualization frameworks. Machinery for processing and manipulating relational tables can be applied to network data, including query processing, creation of derived columns (*e.g.*, using the *Expression* pattern, §2.6), and the use of *Cascaded Tables* (§2.3). The same node table can be reused across multiple graphs, while edge data can be swapped in and out of an existing graph. Furthermore, this representation directly maps to the format commonly used in database systems, facilitating visualization of network data stored in a relational format.

However, use of the *Relational Graph* pattern does introduce new obstacles. First is the issue of performance, particularly for traversing the graph structure. Properly indexing the key fields can significantly improve performance, but involves an overhead that may be unacceptable for large graphs. As a result, *Relational Graph* implementations often include acceleration structures. The InfoVis Toolkit [12] adds auxiliary columns to node and edge tables, maintaining references to "next" and "previous" edges and storing statistics such as node degrees. Prefuse [14] maintains a separate table within the Graph object, storing adjacency lists and node statistics. Finally, the *Relational Graph* pattern replaces the familiar object-oriented model of graphs, potentially complicating programming tasks. This deficit can be addressed using the *Proxy Tuple* pattern (§2.5).

2.5 Proxy Tuple

Use an object-relational mapping for accessing table and network data sets, improving usability and data interoperability.

While patterns such as *Data Column* (§2.2) and *Relational Graph* (§2.4) improve efficiency, reusability, and extensibility, they introduce abstractions more complicated than the naïve approaches they replace. In particular, working with table relations and graph nodes and edges as simple objects is a more familiar and intuitive model to many programmers. The *Proxy Tuple* pattern provides a solution to this problem, using an object-relational mapping to provide a simple interface for accessing, manipulating, grouping, and reordering table and graph data.

The structure of the *Proxy Tuple* pattern is shown in Figure 6. Instead of accessing table or graph data directly, Tuple instances constitute a proxy object that allows programmers to work with rows, nodes, and edges as simple objects. A Proxy Tuple is a lightweight object storing its row number and references to backing data sets—a table and, if appropriate, a graph. Tuples also provide methods for accessing and manipulating underlying data. Tuple instances can be sorted irrespective of their ordering in the backing table, and can be aggregated and grouped as desired, even combining Tuples from different tables or graphs. Tuples can be created by and stored within a tuple manager associated with the backing table or graph. The manager initializes Tuples as needed and invalidates them when records are deleted.

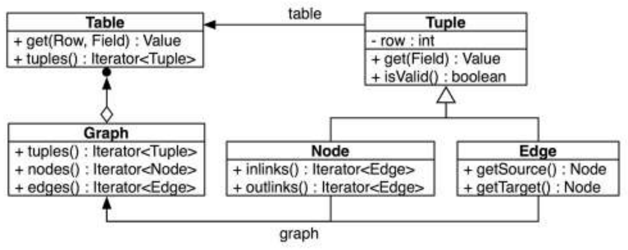


Table
+ get(Row, Field) : Value
+ tuples() : Iterator<Tuple>
table
Tuple
- row : int
+ get(Field) : Value
+ isValid() : boolean
Graph
+ tuples() : Iterator<Tuple>
+ nodes() : Iterator<Node>
+ edges() : Iterator<Edge>
Node
+ inlinks() : Iterator<Edge>
+ outlinks() : Iterator<Edge>
Edge
+ getSource() : Node
+ getTarget() : Node
graph

Figure 6. The Proxy Tuple Pattern. Tuples provide an object-oriented proxy for accessing a row of table data. The Node and Edge subclasses play a similar role for graphs, also enabling traversal of the network structure.

Proxy Tuples can also be used to improve data safety. Consider the case of using an integer value to refer to a table row. If that row is deleted and then later repopulated by a newly inserted row, access using the stored row number will not result in an exception and operations may carry unexpected consequences. A Proxy Tuple, however, can be invalidated immediately upon deletion of its backing row, preventing future access through that object and thus promoting data consistency.

The *Proxy Tuple* pattern is used throughout the prefuse visualization toolkit [14] to manage both abstract data elements and visual items displayed in a visualization. By providing a simplified interface to a complex subsystem, *Proxy Tuple* applies the *Facade* pattern of [13]. Tuple managers associated with a table or graph can employ the *Factory Method* pattern [13] to control the concrete types of instantiated tuples.

2.6 Expression

Provide an expression language for data processing tasks such as specifying queries and computing derived values.

Many visualization frameworks require a basic level of database functionality. Either programmers or end-users may need to specify queries or calculate derived measures from existing data fields. By including an *Expression* language, a visualization framework can support such functionality in a general fashion that can be reconfigured at run-time.

The structure of the *Expression* pattern is shown in Figure 7. The pattern is a direct application of Gamma et al's *Interpreter* pattern [13], customized for data processing needs. Language statements are represented as a tree of Expression objects that perform calculations over data elements. Common expression objects include literal values, arithmetic or comparison operations, and data field references. A Predicate is a special type of Expression that returns values of type boolean.

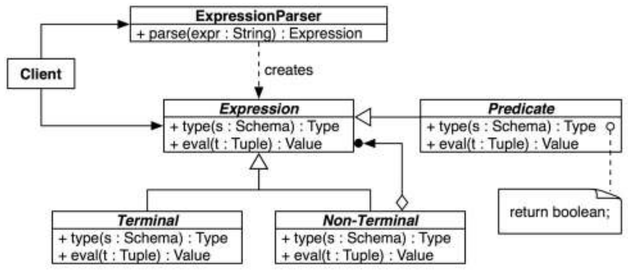

ExpressionParser
+ parse(expr : String) : Expression
Client
creates
Expression
+ type(s : Schema) : Type
+ eval(t : Tuple) : Value
Predicate
+ type(s : Schema) : Type
+ eval(t : Tuple) : Value
return boolean;
Terminal
+ type(s : Schema) : Type
+ eval(t : Tuple) : Value
Non-Terminal
+ type(s : Schema) : Type
+ eval(t : Tuple) : Value

Figure 7. The Expression Pattern. Expression language statements are constructed as a tree of processing objects. Expressions perform calculations over data elements and return the result. Predicate expressions returning values of type boolean can be used to specify queries.

Invocation of an expression causes recursive invocation of sub-expressions, with resulting values propagating up the expression tree to calculate the final result. Expressions may be used to specify selection queries (as Predicate expressions), create derived data fields (*e.g.*, using a concrete *Data Column* (§2.2) instance that refers to an Expression instance), or perform other data processing tasks. The structural diagram depicts Expressions that take a single tuple as input. Single tuple expressions are sufficient for a range of useful calculations, though expanded contexts may be desired, for example to compute joins across tables.

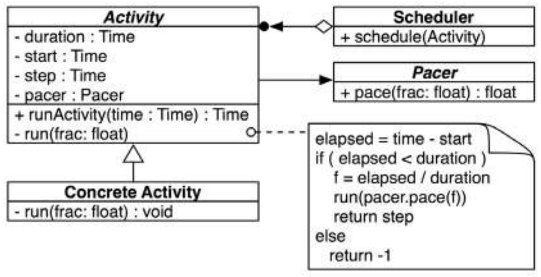
Operations upon the expression tree itself can also be of great use. For example, traversals of the tree can be used to identify referenced data fields, compute optimized query plans for a Predicate, or print a text representation of the expression (also useful for generating queries to external databases). Such operations could be encapsulated within objects in accordance with Gamma et al's *Visitor* pattern [13].

There are multiple means of constructing an expression tree. Individual objects can be manually instantiated and assembled into the expression tree. An ExpressionParser can be provided to compile text strings written in a textual expression language into the tree of objects. This approach is used in both Polaris (now Tableau) [20] and prefuse [14]. Another possibility, used in the Improvise framework [23], is to graphically represent the expression tree and allow users to edit expressions in a direct manipulation fashion.

2.7 Scheduler

Provide schedulable activities for implementing time-sensitive, potentially recurring operations.

Dynamic visualizations often make use of time-sensitive, recurring operations. The most common example is animation, which requires updating visual properties and redrawing the display at regular time intervals, usually over a specified duration. Other examples include time-sensitive responses to user input and computations bounded to a specified time duration (*e.g.*, an iterative graph layout). The *Scheduler* pattern provides a solution that enables time sensitive operations and supports extensibility.



```
elapsed = time - start
if ( elapsed < duration )
  f = elapsed / duration
  run(pacer.pace(f))
  return step
else
  return -1
```

Figure 8. The Scheduler Pattern. Activity instances are registered with a centralized scheduler that runs the activities over a specified time interval, repeatedly running the activity at requested time steps.

The structure of the scheduler pattern is shown in Figure 8. Custom operations are created by subclassing the abstract Activity class and implementing the "run" method (an example of the *Template Method* pattern [13]). An Activity has a specified start time, a duration, and a step time defining the desired length of time to wait between repeated invocations. The run method takes as a single argument a fractional value between zero and one that indicates the progress of the Activity within its duration. This value can increase linearly as time elapses or can be modified through the use of a pacing function. Slow-in, slow-out animation can be achieved using a pacing function with a sigmoidal shape.

The *Scheduler* pattern has been used extensively in visualization and user interface frameworks. The Information Visualizer [5] included a "governor" that oversaw animation and adjusted the level of detail when activities took longer than desired. Hudson and Stasko [15] used the *Scheduler* pattern to provide animation within the Artkit user interface toolkit, introducing the use of pacing functions. More recent frameworks, including Piccolo [3] and prefuse [14], use the pattern.

An important issue in implementing the *Scheduler* pattern is choosing how to handle concurrency. A common approach is for the Scheduler's dispatch loop to run in a dedicated thread. The Piccolo toolkit takes a different approach. Its scheduler runs within the user interface event loop, resulting in a single-threaded model that frees programmers from explicitly handling concurrency issues. However, this approach carries the drawback that greedy activities with long-running "run" methods will leave all user interface components unresponsive, regardless of their relation to the visualization. Prefuse attempts a compromise between these models, maintaining a separate scheduling thread but performing automatic locking in both input controllers and schedulable visualization operators to help shelter programmers from concurrency issues.

2.8 Operator

Decompose visual data processing into a series of composable operators, enabling flexible and reconfigurable visual mappings.

When designing object-oriented visualization software, developers must decide upon the appropriate level of granularity for the visualization components of their system. Visualization frameworks such as Advizor [11] and the InfoVis Toolkit [12] adopt a model similar to traditional user interface toolkits, encapsulating different visualization designs into monolithic "widgets". The result is a library of interactive components such as scatterplots, time-series charts, or treemaps that can be directly instantiated and then added to the user interface. Creating new visualizations requires subclassing existing widgets or writing entirely new components. An alternative approach is to target a finer level of granularity using an *Operator* pattern. The idea is to deconstruct visualization tasks into composable operators whose configuration can be modified at run-time. Example operators include layout algorithms, visual encodings, and distortion techniques. New visualizations can be constructed by composing existing operators and/or introducing new operators, facilitating reuse at the level of individual visualization techniques. The prefuse toolkit [14], for example, includes a demonstration of composing layout operators to create custom hybrid layout schemes. Operators also simplify many customization tasks, allowing clients to directly modify the set of operators that constitute the visualization.

The structure of the *Operator* pattern is shown in Figure 9. The basic structure is intentionally quite simple. An operator has a single required method that performs the operation (an instance of the *Template Method* pattern [13]), simplifying the creation of new, general-purpose operators. An operator performs processing on a Visualization instance. Operators may maintain a reference to the Visualization (as pictured), or have the Visualization passed as a parameter to the "operate" method (if stateless operators are desired). An individual operator may have any number of additional parameters, depending on its function. For example, a color encoder might include a color palette used to determine color values of items retrieved from the visualization. Operators can be aggregated into composites, enabling sequential batch execution or conditional evaluation of operators.

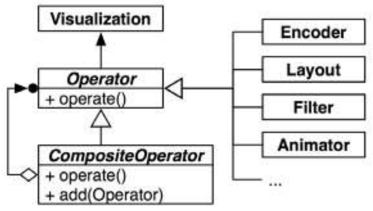


Figure 9. The Operator Pattern. Operators are modules that perform a specific processing action, updating the contents of a visualization in accordance with a data state model [8]. Possible operators include visual encodings (for size, shape, color, etc), spatial layout algorithms, visibility filters, and animated interpolation. Composite operators aggregate individual operators to enable sequential or conditional execution.

Operators may be implemented as Activity instances in the *Scheduler* pattern (§2.8), enabling time-sensitive or recurrent invocation. Once schedulable, operators can additionally be used to implement animated transitions, as done within the prefuse toolkit [14]. Operators can also employ *Expressions* (§2.6). For example, a Predicate could be used to select a group of visual items for the operator to process. It is possible to implement operators within the *Expression* language itself, an approach partially supported in Improvise [23].

As described here, the use of operators fits squarely within the *data state* model defined by Chi [8]. The operators act upon the visualization, whose state updates as a result. Another variant of the operator pattern is the *data flow* model. Data flow operators have specific input and output types and are chained together in directed acyclic graphs to define processing flows. This approach is used in a number of 3D visualization frameworks, including the Visualization Toolkit [19]. Chi [9] has demonstrated that applications written in one model can be equivalently formulated in the other. We focus on the data state model due to its greater prevalence in information (as opposed to scientific) visualization.

2.9 Renderer

Separate visual components from their rendering methods, allowing dynamic determination of visual appearances.

Standard user interface toolkits use a component or "widget" model, in which interactive components are represented as individual objects responsible for drawing themselves and handling user input. Typically, such components include a "paint" method that issues the drawing commands for rendering the object onscreen. Changing the appearance of a component often requires subclassing that component and overriding the paint method. This approach is common in many visualization frameworks. For example, each visual item in the Piccolo toolkit [3] has its own paint method, and each visualization provided by the InfoVis Toolkit [12] is implemented as a stand-alone widget. This approach has the advantages of low overhead, familiarity, and simplicity. However, it also limits dynamic changes in appearance. For example, implementing a semantic zoom in the standard model requires either (1) creating entirely new sets of objects and swapping them based on the current zoom level or (2) creating a subclass with a custom paint method that explicitly handles each zoom level. The *Renderer* pattern solves this problem by decoupling the representation of a visual item from its rendering, enabling dynamic, run-time changes in visual appearance.

The structure of the *Renderer* pattern is shown in Figure 10. Rendering of visual items is performed by dedicated, reusable modules responsible for mapping the item's visual attributes into actual pixels. Renderers perform the view transformation step of Card et al's *infovis reference model* [6]. In addition to a drawing routine, a Renderer should also provide access to the pixel-level geometry, testing if a given point is contained within the item (useful for identifying when an item is underneath the mouse pointer), and calculating bounding boxes. Visual items might contain a direct reference to their current Renderer, or, as illustrated in Figure 10, a RendererFactory can be used. The RendererFactory dynamically assigns Renderers to items based on current conditions. The *Renderer* pattern supports extensibility through the introduction of new Renderers.

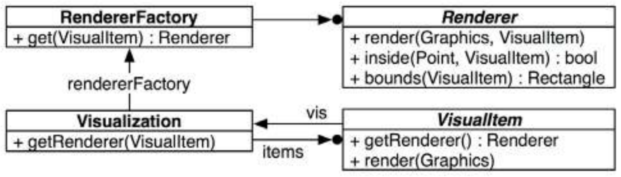

RendererFactory
+ get(VisualItem) : Renderer
rendererFactory
Renderer
+ render(Graphics, VisualItem)
+ inside(Point, VisualItem) : bool
+ bounds(VisualItem) : Rectangle
Visualization
+ getRenderer(VisualItem)
vis
items
VisualItem
+ getRenderer() : Renderer
+ render(Graphics)

Figure 10. The Renderer Pattern. The mapping between items and their visual appearance is determined using Renderer modules, responsible for drawing, interior point testing, and bounds calculation. A RendererFactory can be used to assign Renderers to items based on current conditions, such as data attribute values or the zoom level.

Modular renderers have been applied in various frameworks to allow clients to extend or change rendering behaviours of provided widgets. For example, the Java Swing user interface toolkit uses a *Renderer* pattern to allow clients to specify the rendering behavior of individual items within Swing JTable and JTree widgets. The prefuse toolkit [14] uses the *Renderer* pattern for drawing visual items, using a RendererFactory to dynamically assign Renderers to visual items. The *Renderer* pattern can also be used in conjunction with other patterns. RendererFactory instances can apply the *Production Rule* pattern (§2.10) to provide customizable rule sets for Renderer assignment. By pooling and reusing individual Renderers for use with any number of items, a RendererFactory applies the *Flyweight* pattern [13].

2.10 Production Rule

Use a chain of if-then-else rules to dynamically determine visual properties using rule-based assignment or delegation.

In many design scenarios, a designer may specify numerous default settings and then override these settings to deal with special cases. For example, Cascading Style Sheets (CSS) are a widely-used technology enabling web designers to specify document properties such as typeface, color, and alignment and then override these settings as needed. Special cases could include custom settings for a particular class of document elements or events such as a mouse over. Similar needs arise in visualization software. For example, a particular color encoding may be desired by default, but overridden in special cases such as user interaction or inclusion in search results. Writing a custom color encoding to handle these cases would be an inefficient use of time and unnecessarily bloat the software with more class definitions. The *Production Rule* pattern provides a flexible solution to this need.

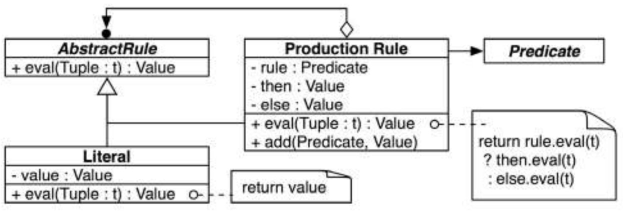


Figure 11. The Production Rule Pattern. A series of nested rules can be used to return individual values that meet desired conditions.

The structure of the *Production Rule* pattern is shown in Figure 11. Given a data item (*e.g.*, a Tuple instance) as input, a rule set tests the data item against the conditions and returns a matching value. Rule sets can begin with a default value; new conditions and values can then be added to handle special cases. The result is a dispatching structure employing Gamma et al's *Chain of Responsibility* pattern [13]. Production rules can be modified at run-time, allowing the rule set to change while an application is running, possibly as a result of user interaction. As formulated here, the implementation of *Production Rule* uses predicate objects to encapsulate the rule conditions. When used in conjunction with the *Expression* pattern (§2.6), not only the predicates, but the entire rule structure may be implemented using expression constructs (*i.e.*, using "if" statements).

Other visualization software patterns can benefit from the use of production rules. An implementation of the *Renderer* pattern (§2.9) may use production rules to assign renderers to visual items. The *Operator* pattern (§2.8) can use production rules for visual encoding operators. For example, a color encoding might use a production rule that evaluates to a specific color value in one condition (*e.g.*, a color indicating a mouse-over event) but to a delegate color encoding by default (*e.g.*, a nominal color encoding based upon a data attribute). Both of these approaches are used within the prefuse toolkit [14].

2.11 Camera

Provide a transformable camera view onto a visualization, supporting multiple views and spatial navigation of data displays.

Spatial navigation operations, such as panning and zooming, are often used to explore large data sets. Such techniques are often applied in conjunction with multiple views, for example to create overview+detail displays. A common approach to implementing such functionality is to treat the data display as a camera within the geometric space of the visualization. Moving, zooming, or rotating the camera accordingly changes the viewpoint seen by users. Multiple cameras can be used with a single visualization, enabling multiple views with unique perspectives.

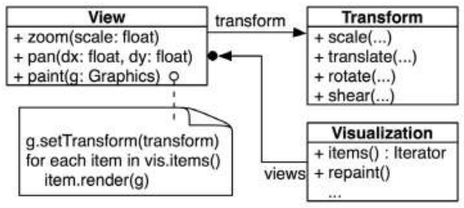


Figure 12. The Camera Pattern. A view component maintains an affine transformation matrix that is applied to visual items when rendering. The affine transform matrix can be used to specify translation, rotation, scale, and shearing transformations on the geometry of the view.

The structure of the *Camera* pattern is shown in Figure 12. A view instance (a user interface component providing a graphics canvas) maintains an affine transformation matrix describing the current position, scale, and orientation of the camera view. When the display draws itself, all graphics operations are subject to this transform. As most modern 2D and 3D graphics libraries allow transformation matrices to be applied directly to a graphics context, this can be implemented in a straightforward way. Multi-view displays are created by instantiating any number of view components and setting their transforms.

The camera pattern has a long history of use in graphics libraries such as OpenGL and is found in nearly any framework that supports geometric zooming, such as Piccolo [3] and prefuse [14]. One limitation of the pattern is that it only supports affine geometric transformations. Non-geometric techniques, such as semantic zooming, can instead be implemented by changing the rendering behavior of visual items in response to the transform settings. Dynamic rendering behavior can be implemented in a modular and extensible manner using the *Renderer* pattern (§2.9). Animated view transitions can be achieved using the *Scheduler* pattern (§2.7); activity instances can incrementally update the view transformation and trigger repaints.

2.12 Dynamic Query Binding

Allow data selection and filtering criteria to be specified dynamically using direct manipulation interface components.

Dynamic queries are a central technique in information visualization, allowing users to refine a data view through direct manipulation [1]. Any number of user interface widgets, such as sliders, range sliders, checkboxes, and text boxes may be used to input query conditions. The *Dynamic Query Binding* pattern describes the mechanisms by which one can easily create one or more widgets bound to a general-purpose query predicate, automatically updating both the predicate and any other bound components when interaction occurs.

The structure of the *Dynamic Query Binding* pattern is shown in Figure 13. As pictured, a particular data set and a field of interest are used as input to a dynamic query binding that maintains both a selection predicate and a data model. The data model participates in a *Model-View-Controller* pattern [16] and provides coordinated state for any number of dynamic query widgets. The concrete implementation of the model might store a bounded range of values, a list of selected items, or a textual search query. By providing *Factory Methods* [13], the dynamic query binding can instantiate and configure user interface widgets at the client's request. For example, a range query binding might provide methods for creating appropriately configured range sliders. As users interact with these widgets, changes to the data model result in notifications to the dynamic query binding, which then updates the query predicate. Other observers can in turn be notified of changes to the predicate and take action accordingly. By explicitly representing query criteria as a predicate (possibly applying the *Expression* pattern, §2.6), dynamic queries can be used in a very general fashion. The predicate could be used to control item visibility, as is typically done, or as criteria for any number of alternative visual encoding or data processing operations.

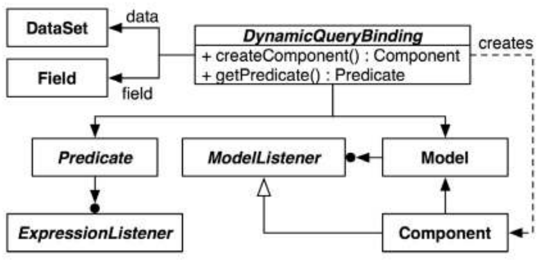


Figure 13. The Dynamic Query Binding Pattern. Given a data set and data field as input, a dynamic query binds a selection predicate to a data model. The data model can be used as the backing state for any number of user interface widgets. The binding also serves as a factory for creating and configuring an appropriate set of dynamic query widgets.

Although most infovis frameworks provide support for dynamic queries, not all implement them in full generality. Some frameworks, such as the InfoVis Toolkit [12], do not provide generalized query predicates and so instead must update data structures directly, reducing the applicability of the pattern. An implementation might also forego using the *Factory Method* pattern, instead requiring clients to instantiate and configure the user interface widgets on their own. Alternatively, one might maintain a single instantiated widget instead of a backing model. By maintaining a backing data model, the general form of the pattern supports any number of coordinated components. Various widgets can be generated from a single binding and incorporated into different parts of an interface. All affect the same query predicate and simultaneously update in response to changes originating at any of the other bound widgets.

3 Conclusion

While many of the patterns presented can be fruitfully applied in isolation, it is often in the relationships among patterns that their greatest value is realized. For example, combining the *Scheduler* (§2.7) and *Operator* (§2.8) patterns enables the creation of reusable animation operators, while combining the *Relational Graph* (§2.4) and *Proxy Tuple* (§2.5) patterns provides a programmer-friendly interface to a powerful and flexible data representation. Figure 14 provides a partial illustration of the relationships between the patterns discussed in this paper, including both the proposed visualization patterns and related patterns from Gamma et al. [13]. The figure provides a roadmap to applying patterns in a holistic fashion.

Given the limited format of this paper, a great deal of discussion and a rich space of examples had to be curtailed. Each pattern warrants a longer discussion than we have provided here. In addition, some candidate patterns have been left out. For example, the *Scenegraph* abstraction used in 3D toolkits such as VTK [19] and 2D toolkits such as Piccolo [3], can be usefully described in a pattern format. We would also note that observing patterns within real world source code plays an important part in understanding the value of pattern-infused design. Interested readers may wish to explore one or more of the visualization frameworks freely available online, including Improvise [23], the InfoVis Toolkit [12], Piccolo [3], prefuse [14], and the Visualization Toolkit [19].

Finally, we reiterate that patterns are not static entities, but evolving descriptions of best practices. We make no claims as to the finality or completeness of the patterns presented here, only to their observed effectiveness in visualization contexts. We look forward to these and other patterns being proposed, challenged, refined, and applied.

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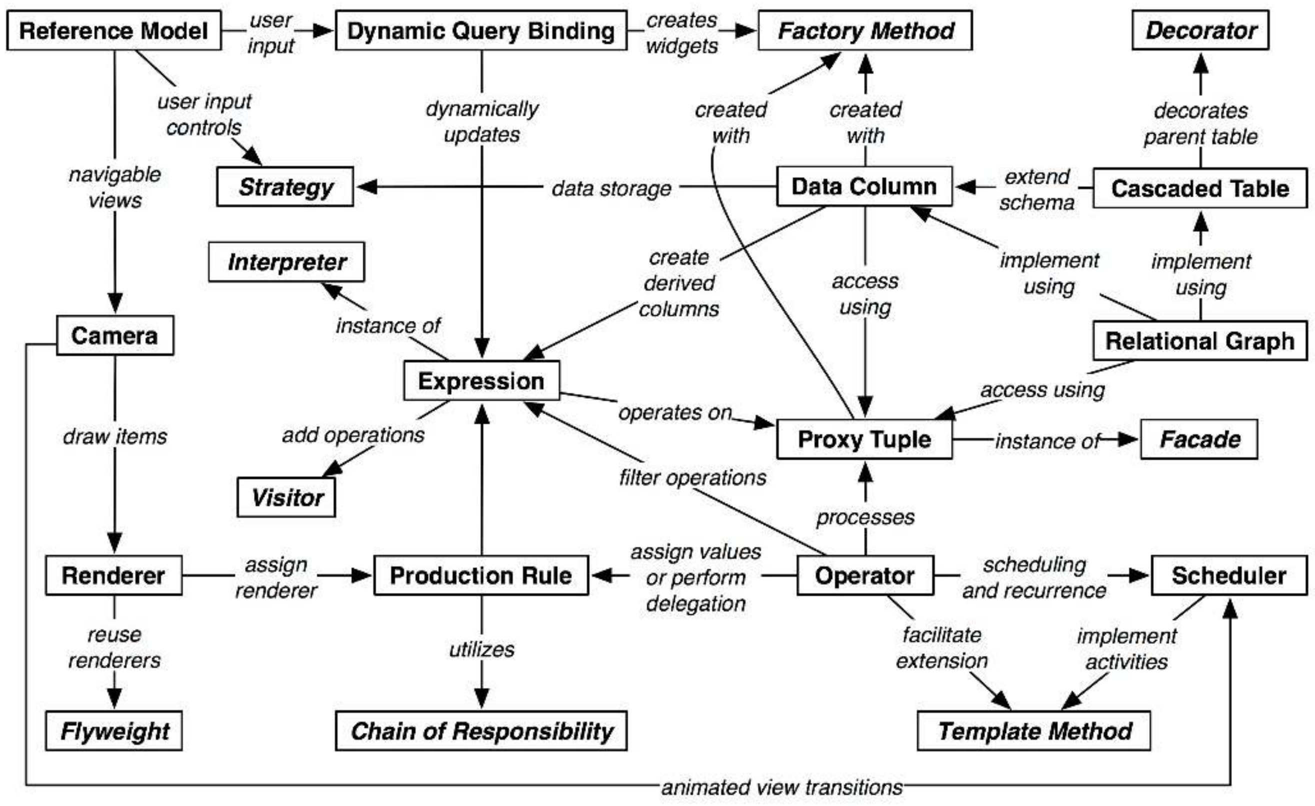

Figure 14. Design Pattern Relationships. The network depicts interactions between design patterns, intending a more holistic pattern of how the various patterns apply or mutually reinforce each other. Patterns with italicized text (*e.g., Flyweight*) are taken from Gamma et al. [13]; those with a standard typeface were introduced in this paper. To simplify the diagram, patterns used extensively by the visualization patterns (*e.g., Observer*) have been omitted.

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