From Graph Transformation to
Rule-based Programming with Diagrams*

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Abstract. Graph transformation is a well studied computational model for specification and programming. In this paper we outline a path that can be taken in order to turn graph transformation into a rule-based language for programming with diagrams. In particular, we discuss how data abstraction and functional abstraction can be achieved in the setting of graphs, by minimal extensions of the underlying graph and transformation model.

1 Introduction

The rule-based transformation of graphs is a well studied field of theoretical computer science, see [25]. Graph transformation (also known as graph grammar theory, and graph reduction) has been applied successfully for modelling software systems and studying their behaviour, see [12].

So far, PROGRES [28] is the most successful programming language and system based on graph transformation. It supports functional abstraction, control structures (including backtracking), and encapsulation. However, PROGRES and other graph transformation languages still have some deficiencies:

- Graphs, their central data structures, are flat; they may not contain other graphs as components. The concept of aggregation is missing.
- Most of their programming concepts have only been added as textual constructs, on top of the graph transformation mechanism. Thus relevant parts of the languages are no longer graphical and rule-based.

We believe that a graph transformation language needs both features if it shall compete with visual object-oriented programming languages. Therefore we extend graphs by an aggregation concept, and lift a simple graph transformation mechanism to this model. Then we introduce functional abstraction, control, typing, and graph-oriented encapsulation, by slight modifications to the graph

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model and transformation mechanism. The resulting language proposal is still completely graphical and rule-based.

The paper is organized as follows: Graphs and a simple way of graph transformation are introduced in section 2, and extended by a concept for graph aggregation in section 3. Concepts for functional abstraction and control are proposed in section 4, and some ideas concerning typing are outlined in section 5. Then, in section 6, we show how subgraphs and transformations can be encapsulated in classes. We conclude with some remarks on related and future work.

Due to space limitations, the presentation is informal. The concepts are explained by a running example concerned with the graphical representation of queues and queue operations.

2 Graph Transformation

We introduce a notion of graphs, and graph transformation that is simple, and yet expressive enough to form the basis for specification and programming.

2.1 Graphs

Graphs represent relations between entities as edges between nodes. Usually, edges link two nodes. We, however, allow edges that link any number of nodes, and label them so that different relations, of any arity, can be represented in a single graph. We also allow that a sequence of nodes, called points, may be designated as the interface of a graph at which it may be glued with other graphs. In the literature, such graphs are known as pointed hypergraphs [16, 7].

Example 1 (Queue Graphs). The structure of queue graphs is represented by two kinds of edges: a Q-labelled edge is linked to the begin and end node of a chain of I-labelled edges; every I-labelled edge is in turn linked to the begin and end node of an item graph that is stored in the queue.

Figure 1 shows how graphs are depicted in this paper. Nodes are drawn as circles, and filled if they are points. Edges are drawn as rectangles around their label, and are connected to their attachments by lines that are ordered counterclockwise, starting at noon. The rectangles for binary edges with empty labels "disappear" so that they are drawn as lines from their first to their second linked node.

We abstract from some graph features although they are important in practice:

- Typing is only considered as far as it makes our constructs and definitions well-defined. Section 5 discusses some further issues.
- Attributes are values that may be associated to nodes and edges in order to represent non-structural properties of a graph. We do not consider attributes here although they will be used in implementations, e. g. for computing the layout of graphs.
Fig. 1. A pointed graph

- **Notation and layout** of graphs is often tailored towards a particular application domain. Such conventions for the drawing of nodes and edges define diagram languages. We restrict ourselves to the graph notation explained above, and refer to DiaGen [22] for a system that allows to specify diagram languages for the kind of graphs considered here.

### 2.2 Rules and Transformation

We use a simple kind of gluing graph transformation [9] that is compatible with a restricted form of substitution-based graph transformation [17].

A **graph transformation rule** $t : P \rightarrow R$ (rule for short) consists of a pattern graph $P$, and a replacement graph $R$. A transformation step from a host graph $G$ to some graph $H$ via a graph transformation rule $t$ is written $G \xrightarrow{t} H$ and proceeds as follows:

- **Match** the pattern graph $P$, i.e. find a subgraph $P'$ in $G$ that is a copy of $P$.
- **Check** that every node in $P'$ which is linked to an edge outside $P'$ corresponds to a point of $P$. (Otherwise, the clipping described below would leave some edges with dangling links.)
- **Clip** $P'$ by removing it up to its points, to obtain the context graph $C$.
- **Glue** a copy $R'$ of the replacement graph $R$ to $C$ by identifying the points of $P'$ with the corresponding points of $R'$, to obtain the transformed graph $H$.

A graph may host several matches, of several rules. Thus graph transformation is nondeterministic in general. This gives a potential for concurrency: Several matches of rules can be replaced in parallel if they are independent in a certain sense, see e.g. [9].

**Graph transformation** with a set $\mathcal{T}$ of graph transformation rules considers sequences of sequential transformation steps in arbitrary order, and of arbitrary length. (We ignore concurrency, as an independent parallel step corresponds to a sequence of sequential steps.) If there is a transformation sequence $G_0 \xrightarrow{t_1} G_1 \xrightarrow{t_2} \cdots \xrightarrow{t_n} G_n$, we write $G_0 \Rightarrow^*_T G_n$, and say that $\mathcal{T}$ transforms $G_0$ to $G_n$.

Graph transformation can be used to define **graph languages**, analogous to Chomsky grammars, as the set of all terminal graphs $G$ into which $\mathcal{T}$ transforms some distinguished start graph $S$, where terminality is usually defined by the absence of certain (“nonterminal”) labels in a graph.
Graph transformation can be used to specify a \textit{function} on graphs, like term rewriting [19] specifies functions on terms, by taking an arbitrary graph as input, and transforming it as long as possible. This function is \textit{partial} if certain graphs can be transformed infinitely, and \textit{nondeterministic} if a graph may be transformed in different ways.

It is this last way of using graph transformation that is the basis for programming with graph transformation, but language generation is useful too, for typing (see section 5).

\textit{Example 2 (Queue Graph Transformation).} Figure 2 shows a rule that \textit{dequeues} the first item graph of a queue graph, Figure 3 shows how this rule transforms the queue graph in Figure 1. The occurrences of the pattern and replacement graphs in the host graph, and transformed graph are drawn with fat lines.

\begin{figure}[h]
\centering
\includegraphics[width=0.3\textwidth]{fig2.png}
\caption{A dequeuing rule}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.3\textwidth]{fig3.png}
\caption{A dequeuing step}
\end{figure}

This representation of queue graphs is not really adequate. It provides no general answer to the question: \textit{What is the item graph linked to some l-edge?} In Figure 3, we could assume that an item frame designates all nodes and edges connected to both its begin and end node. Then, queues could only be used to store connected graphs, which might be too restrictive. (We could link l-edges to \textit{all} nodes that belong to the item graph; then it would still be open \textit{which} of the edges between those nodes in the host graph belong to the item graph.)

\section{Structured Graphs}

The graphs considered so far are \textit{composite} values, but \textit{flat}; Their components, nodes and edges, are primitive; none of them may be a graph again. That is the
general problem when graphs shall be composed from subgraphs, like the queue and item graphs in Example 2 above. To overcome this limitation, we introduce compound edges that may contain graphs, and extend graph transformation correspondingly.

3.1 Hierarchical Graphs

A hierarchical graph consists of a graph as considered before, called its top-level graph, wherein some edges, called frame edges (or just frames), contain graphs that may be hierarchical again.

The hierarchical graphs that occur in rules may furthermore contain variable edges as placeholders for graphs. Variable edges bear distinguished labels, called variable names. A mapping $\beta = \{X_1 \mapsto G_1, \ldots, X_n \mapsto G_n\}$ that associates hierarchical graphs $G_i$ with variables names $X_i (1 \leq i \leq n)$ is called a binding. The instantiation of a hierarchical graph $G$ according to a binding $\beta$ is denoted by $G^\beta$, and obtained by removing every $X_i$-edge $x$ in $G$, and gluing a copy of $\beta(X_i)$ to the nodes that were linked to $x$.

Example 3 (Hierarchical Queue Graphs). For a hierarchical graph representation of queues, we turn the Q- and L-edges of Examples 1 and 2 into frames that contain queue and item graphs, respectively. Frames are rectangles (like ordinary edges), with their contents drawn inside; they are filled in different shades of grey, and their labels are omitted. Variable names appear in italics.

Figure 4 shows two queue graphs. The graph on the left hand side contains a variable $X$, and the graph on the right hand side is its instantiation with the binding $\{X \mapsto \text{[[ ]]}.\}$.

![Fig. 4. Two hierarchical queue graphs](image)

In this representation, item graphs are always complete (clippable) subgraphs that are disjoint to each other. This helps to maintain the consistency of the representation. Note that item frames may contain graphs of any arity; in Figure 4, they have 1, 2, or 0 points.

To keep the presentation simple, we do not consider compound nodes that may contain hierarchical graphs. Such nodes can be simulated by unary frame edges pointing to plain nodes. In a real programming language, however, compound nodes should be supported, if only for symmetry.
3.2 Hierarchical Graph Transformation

In a hierarchical graph transformation rule (hierarchical rule, for short) \( t : P \rightarrow R \), the hierarchical pattern and replacement graphs \( P, R \) may contain variables, but every variable name occurring in \( R \) must occur in \( P \) as well, and every variable name may occur at most once in \( P \).

The transformation of hierarchical graphs is then performed as follows:

- **Match** the top-level of the pattern graph \( P \), either on the top-level of the host graph \( G \), or recursively in the contents of some of its frames; then match the contents of every frame in \( P \) recursively with the contents of the corresponding frame in \( G \).
- **Bind** the variables in \( P \) during matching, e.g. construct a binding \( \beta \) such that \( P'\beta \) is a subgraph of \( G \).
- **Check** whether \( P'\beta \) isippable.
- **Clip** \( P'\beta \) to obtain the context graph \( C \).
- **Glue** an instantiated copy \( R\beta \) of the replacement graph \( R \) to \( C \).

It should be noted that the **Bind** step requires **graph parsing** which is not defined in general. However, for the typing considered in section 5, parsing algorithms exist, even if they are not efficient.

**Example 4 (Hierarchical Queue Graph Transformation).** Figure 5 shows two hierarchical graph transformation rules for enqueuing and dequeuing. Figure 6 shows an enqueuing transformation, followed by a dequeuing transformation.

\[ Q \rightarrow X \quad \rightarrow \quad Q \rightarrow X \]

\[ X \rightarrow Q \quad \rightarrow \quad Q \]

**Fig. 5.** Hierarchical rules for enqueuing (top) and dequeuing (bottom)

The variables \( Q \) and \( X \) binds queue graphs, and item frames, respectively. Enqueuing *duplicates* an item frame with its entire contents, by duplicating the variable \( X \) in its replacement graph; dequeuing *deletes* an item frame, again with its contents, by deleting \( X \) in its replacement graph.

Note that the time required for enqueuing and dequeuing does not depend on the length of the queue, whereas at least one of these operations would need at least logarithmic effort in a term rewriting implementation [6].
4 Abstraction and Control

Graph transformation provides no explicite way to compose transformations from simple ones, and no means to control the order in which rules shall be applied. We introduce transformation predicates as a means to structure and parameterize transformations. We extend rules by application conditions, and show that this can be used to specify control flow.

4.1 Transformation Predicates

A graph transformation rule $t$ can only “call” other rules by indicating, in its replacement, places where other rules shall be applied later. This can be done by inserting a $p$-labelled edge $e$ in the replacement of $t$ that appears in the pattern of a rule $t'$ that shall be applied there. The label $p$ can then be considered as the name of $t'$, and $e$’s links indicate the parameters to which it shall be applied.

We distinguish certain labels as predicate names. A graph transformation predicate (or just predicate) consists of a predicate name $p$ that is associated with a set of graph transformation rules, called its body. Every pattern in the body of $p$ contains exactly one $p$-labelled edge. An edge labelled by a procedure name is called a button edge (or just button), and is depicted as an oval.

Predicates are called by inserting buttons into the start graph of a transformation, or into the replacement graphs of rules and predicates.

A predicate is applied by applying a rule of its body to one of its calls in the host graph. A predicate is evaluated by applying it, and evaluating all predicates that are called in its replacement, recursively.

The links of a button point to the parameters of the transformation predicate. A parameter can be just a node, or an edge with its linked nodes. In particular, such an edge can be a frame that contains a graph parameter (as in Example 5 below), or a button that denotes a predicate parameter (as in Example 6 below). Thus buttons are meta edges; they may not only have links to nodes, but also meta links to other edges or to meta edges.
4.2 Success and Failure

The application of a predicate is very similar to the application of simple graph transformation rules. However, for a transformation predicate, the following question arises: What happens if a predicate is called, but none of its rules applies? This situation can be handled in one of the following ways:

- The transformation predicate, or its call, is considered erroneous, and transformation aborts.
- The call is considered to fail, and cancelled so that another rule may be applied instead.
- The call is considered to succeed, and transformation may continue.

The first interpretation is that of functional languages, and the latter ones are used in logical languages. We allow both. In any case, buttons are always removed during the transformation because they are meta edges that are just introduced to control the program’s execution, but shall not be part of the graphs it computes.

Success, failure and abortion of a transformation predicate are specified in its body: We require an otherwise definition (starting with a “//” symbol), followed by one of the symbols “+”, “-”, or “⊥”, for success, failure, and abortion, respectively.

So we refine the application of predicates as follows: Whenever it turns out that no rule applies to a button, the predicate’s otherwise definition is interpreted as described above.

Example 5 (A Graph Transformation Predicate). In Figure 7 the rule of Example 4 is re-specified as a transformation predicate dequeue that is parameterized by queue frames.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{ dequeue.png}
\caption{The transformation predicate dequeue}
\end{figure}

The body of dequeue contains a single rule; its otherwise definition “// → ⊥” leads to failure if it is applied to an empty queue.

4.3 Application conditions

A transformation predicate can be applied as soon as one of its pattern graphs matches a clipppable part of the host graph. All predicates inserted by the application can then be called in arbitrary order. However, the application will often
succeed only if some of these predicates evaluate successfully. It makes sense to
evaluate them first, before attempting to evaluate the rest.

We extract these "critical" predicates calls as application condition, and de-
ote a conditional rule as \( t : P \mid A \rightarrow R \). It is applied as follows: If the pattern
graph \( P \) matches, its application condition \( A \) is glued to the host graph, and
evaluated completely. Only if this succeeds, the pattern occurrence \( P' \) is replaced
by a copy \( R' \) of the replacement graph \( R \); otherwise, the rule is not applicable,
and the remainders of \( A \) are removed.

Figure 8 below shows a predicate with a conditional rule.

### 4.4 Control

Transformation predicates already provide two simple control mechanisms:

- Pattern matching and otherwise definitions allow for case distinction.
- Applicability conditions specify which predicate calls in a rule are evaluated
  first.

With recursion, and by using combinator predicates that have predicate par-
terms, this suffices to specify control within the language.

**Example 6 (A Control Combinator).** Figure 8 shows a control combinator \( \text{normalize} \) that applies to a transformation predicate denoted by the variable \( T \),
evaluates \( T \) as an application condition, and, if that succeeds, calls itself recur-
sively. As \( T \) shall bind to predicate calls with any number of parameters, we use
the dot notation to indicate that \( T \) links to a varying number of nodes. Where
the \( T \)-button is used as a predicate parameter, it is disguised as an ordinary edge
by drawing a frame around its button. This prevents it from evaluation while it
is "carried around" (in the pattern and replacement graph of the rule).

\[
\text{normalize; } \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{.normalize;}
\]

\[
\begin{array}{c}
\text{normalize} \\
\end{array} \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{normalize}
\]

\[
\begin{array}{c}
\text{normalize; } \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{normalize;}
\end{array} \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{normalize;}
\]

\[
\begin{array}{c}
\text{normalize} \\
\end{array} \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \text{normalize}
\]

**Fig. 8.** The control combinator \( \text{normalize} \)

In Figure 9, \( \text{normalize} \) is applied to a disguised call of dequeue. Every application
of \( \text{normalize} \) removes one item frame by evaluating dequeue as an application
condition, until the queue frame contains no item frame, and dequeue fails. The
empty queue graph is represented by a single node; the numbers 1 and 2 attached
to it shall indicate that this node is the first, as well as the second point of the
queue graph.
The use of conditional rules is crucial for the termination of \texttt{normalize}: Had the call of $T$ been inserted in the replacement graph, \texttt{normalize} could loop in its recursion without ever applying $T$. If defined as above, \texttt{normalize} will only loop if $T$ does not terminate.

Other imperative control structures like while loops, or functional combinators like \texttt{map} and \texttt{reduce} as in Haskell [23] can be defined in a similar way. The most common of them should be predefined in the language.

\section{Typing}

Typing specifies how the data of a program is structured, and establishes rules for applying operations to data. These rules can be checked, preferably just by inspecting the program, before executing it, in order to ensure that it is consistent.

\subsection{Graph Structures}

In modern programming languages like Haskell [23], a type definition

\begin{verbatim}
Intlist ::= Nil | Cons Int Intlist
\end{verbatim}

specifies the structure of data recursively. We introduce similar definitions for the structure of graphs.

A distinguished set of labels is used as \textit{type names}, and the \textit{structure} of a \textit{graph type} named $T$ is specified by a \textit{graph structure definition} of the form

\[ T ::= G_1 \mid G_2 \mid \ldots \mid G_n \]

where the graph $T$ consists of a $T$-edge with its linked nodes, and the $G_i$ are graphs that may contain type edges again. Graph structure definitions can be considered as predicates that generate the \textit{graph values} of a type.
Example 7 (Typing Rules for Queue and Item Graphs). Figure 10 defines the graph structure of queue and item graphs.

These graphs may be contained in queue and item frames, respectively. Queue graphs may be bound to queue variables like \( Q \), whereas the variable \( X \) in the previous examples may be bound to a frame containing an item graph. The type \( Q_r \) of queue graphs is \textit{generic}. The type parameter \( \tau \) can be instantiated by any graph type, e.g., to the type \( Q_l \) used in the previous examples.

The rules used for graph structure definitions are a well-studied special case of context-free graph transformation, see [16, 7]. Type checking thus amounts to context-free graph parsing, e.g., as implemented in DiaGen [22].

5.2 Predicate Signatures

The \textit{signature} of a transformation predicate shall specify to which kind of parameters it applies. As predicates are represented as graphs, their signature can be specified by graph structure definitions for a type \( \pi \) of predicates.

Example 8 (Signature of Queue Predicates). Figure 11 specifies the signatures for the predicates used in our examples.

The predicate type \( \pi \) has a varying number of parameter nodes so that the rules of the graph structure definition have different left hand sides. All predicate calls occurring in the examples of this paper can be derived with these rules (together with those of Figure 10). The predicate variable \( T \) used in example 6 is of type \( \pi \).
5.3 Fine-Grained Typing

So far, edges are the only graph components that are typed explicitly, by labelling them with different symbols. In a real programming language, nodes should be typed in the same way. A particular type of edge could then be restricted to have a certain number of links, to nodes of certain types, as in typed graphs [4].

The degree of nodes, e.g. the number of links to some node, could be restricted as well, typically by cardinality expressions like 1, 0..1, 1..n, 0..n. Similarly, the overall number of nodes or edges contained in a graph could be restricted. Such cardinality constraints are allowed in PROGRES [28].

Pointed graphs could be specified to have a certain number of points, of certain types. Then the links of a frame, and the points of its contents could be required to correspond in their number, and their types. A similar correspondence could be required for bindings, between variable edges and graphs, and for rules, between pattern and replacement graphs.

6 Encapsulation

Programming-in-the-large relies on the encapsulation of features in modules so that only some of them are visible to the public, and the others are protected from illegal manipulation. We sketch how graph classes and objects may be added to our proposal, and refer to packages that allow to group classes into subsystems.

6.1 Graph Classes and Objects

A graph class defines a graph type (denoted by the name of the class), and declares graph transformation predicates as its methods. The name of this type, which equals that of the class, and some designated methods are public. The structure of the type, and the other methods, are private.

Example 9 (The Queue Class). In Figure 9 we encapsulate primitive operations on queues within a class.
In this small example, all methods are public. However, the graph structure is visible only inside the class definition, thus adhering to the principle of data abstraction.

Graph objects are frames that contain a graph of some graph class $C$. In other classes, an object can only be manipulated by invoking a method of $C$.

At first glance, information hiding seems to contradict the expectation that the objects of a visual program shall be completely visible to a user. However, information hiding applies only to the program, not to the graphs manipulated in it. This can be defined by views, see [11].

6.2 Graph Packages and Libraries

Experience with object-oriented languages (e.g. Java [2]) has shown that the rather fine-grained encapsulation concept of classes should be complemented with a simple coarse-grained package concept that allows to group a set of related classes in a subsystem. Such a concept can be easily added along the lines of [18], as it just structures the namespace of a program, whithout changing the evaluation.

Then libraries of graph classes can be easily predefined. Also non-graphical values like numbers and strings can be considered as predefined "graph" classes if the language allows graphs to be visualized in a non-standard way, e.g. as text. Then, the language is purely graphical, at least on the conceptual level. (B. Meyer [21] states such a purism principle for object-oriented languages).

7 Conclusion

In this paper we have proposed how a simple notion of graph transformation can be developed towards a programming language. Basically, this has been achieved by distinguishing several kinds of edges:

- Frames allow graphs to be structured hierarchically so that hierarchical subgraphs may be linked via their points.
- Variables bind subgraphs in rules so that they may be deleted or duplicated in a single rule application.
- Buttons allow graph transformations to call each other recursively, with parameters. Based on application conditions and higher-order predicates, control structures can then be defined in the language itself.
- Types define the structure of graph languages and the signature of predicates.
- Objects are frames containing graphs of some type, with methods defined by a graph class. Classes provide for a fine-grained data-driven module concept.

The extensions are graphical, rule-oriented, object-oriented, with some logical and functional flavour (backtracking, and higher order predicates). These ideas could become the kernel of a "complete" graph transformation language that overcomes major deficiencies of today's graph transformation languages.
Related Work

Structured graphs have already been proposed by several authors: The hierarchical graphs of [24, 13] have compound nodes. Pratt [24] considers only language generation similar to Example 7, and Engels and Schürr [13] do not consider transformation at all. Schneider [27] considers graphs that have (simple) graphs as node and edge labels. The graphs of the old AGG system [20] support a rigid layering. Graphs, and the mappings between them can be viewed and manipulated as nodes and edges on the next layer of abstraction. This helps to structure the systems rather than the graph values.

Predicates exist in PROGRES [28], but without graph and predicate parameters. The language also provides textual logical and imperative control structures. FUJABA [15] has graphical control structures, similar to UML [26].

Modules have recently been added to PROGRES; they support functional and data abstraction, but not graph aggregation. We are currently not aware of any other language or language proposal that features graph aggregation and classes. However, the new AGG system [14] and the FUJABA system [15] allow to use object-oriented concepts of their implementation language Java. After all, graph structuring can then be realized by implementing plain graph objects as node or edge attributes of other graph objects.

Future Work

This work is closely related to GRACE [1], a design activity for an approach-independent graph-centered specification and programming language. Specification issues have been ignored here, and complete independence of particular notions of graphs and graph transformation had to be given up because hierarchical graphs require certain properties of graphs. However, although this paper is based on hypergraphs [16] and the gluing approach [3], it is not completely approach-specific: nesting can be defined by adding points, frames and buttons to any kind of graph that has nodes, and a suitable notion of subgraph matching; several transformation approaches can easily be implemented with the rules and predicates proposed here. So we hope that our ideas will be fruitful for GRACE too.

The precise definitions of the concepts presented in this paper has been started in [8] (for frames and hierarchical graph transformation), and will be continued. Some more concepts, like concurrency and distribution, have still to be considered. For plain graph transformation, these concepts have been studied in [29] and [30] so that there is some hope that these results can be extended to our model.

The visualization of graphs, rules, predicates and classes is still very elementary in this paper. A lot of work has to be done in this area if graph transformation shall become a really attractive paradigm for programming and specification. Last but not least, such a language has to be implemented with a comprehensive program development environment.
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References


