# Graphs as Not Only Relational Databases for Behavior Science

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**Abstract**

As researchers, behavior scientists can use many options for data collection, storage, and analysis. Graphs-based data science provides a unified framework that facilitates the understanding of human behavior as a complex system. This article argues for the benefits, utility, and rigor that behavior science can gain as a discipline by adopting graphs as an alternative paradigm to relational databases. The article provides use cases from three APA's division: clinical psychology, consumer psychology, and industrial/organizational psychology.

**Keywords:** key, dictionary, word

**JEL Classification:** D8 , H51

**MSC Classification:** 35A01 , 65L10

## 1 Introduction

In a recent paper, Soto (2025) introduced relational databases for behavior science and used real-world examples to illustrate how relational databases have been used by behavior scientists. Even though relational databases represent the dominant paradigm inside and outside academic research settings, other paradigms are gaining traction (Golino & Epskamp, 2017).

Our work, in contrast, introduces graphs as an alternative paradigm to relational databases, where nodes and arcs (instead of tables and joins) represent the basic elements of any behavior that can be represented as a network or complex system.

Networks have a long history in mathematics as "*graph theory*" (Estrada, 2011). In sociology and social sciences, graph theory is known as "*social network analysis*" (Wasserman & Faust, 1994), and psychologists have levearaged this framework to understand the structure of psychopathology (Borsboom & Cramer, 2013).

## 2 Network as a collection nodes and arcs

One of the easiest way to grasp the idea of a network is by looking its visual representation (see Figure 1). According to Estrada (2011), a network is a collection of points (called nodes) joined together in pairs by lines (called arcs or edges). Scientists can model different kinds of networks from physical networks (e.g., flights between airports) to biological networks (e.g., protein-protein interactions), and social networks (e.g., who follows whom in LinkedIn or X). In this context, the term "social network" should not be confused with online platforms such as Facebook or Instagram, as they are technological implementations that do not necessarily represent all aspects of social networks as an academic discipline.

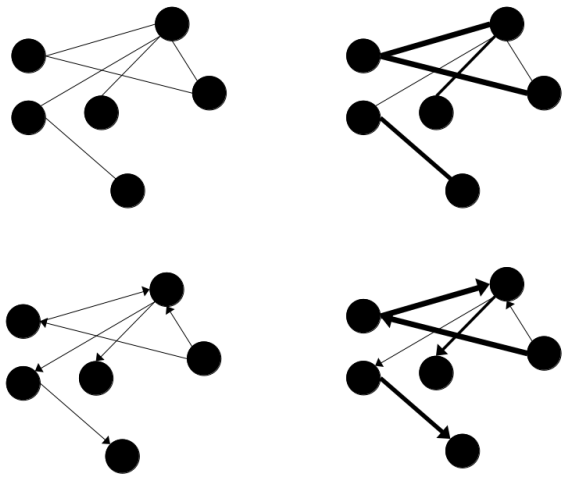

**Fig. 1** A visual representation of four types of simple networks: non-directed unweighted network (upper left), non-directed weighted network (upper right), di- rected unweighted network (bottom left), and directed weighted network (bottom right).

Graphs provide a series of fundamental concepts that facilitate how nodes connect and understand the structure of these links. For example, some networks might look loosely structured which means that it has few connections between nodes and most nodes are isolated or poorly connected. In other cases, the network is densely connected which means that almost all nodes connect with the rest of the nodes. Networks structure is fundamental to a wide range of behavioral phenomena including all kinds of spreads of a disease, all kinds of clustering, and other social behavior including propagation of rumors or fake news.

## 2.1 Configurations

A configuration is a specific pattern of connections between nodes. The most elementary configuration is a dyad (two connected nodes). Other common configurations include triangles (three nodes, all connected to each other) and k-stars (a central node connected to k other nodes). These configurations, along with others, make up the larger connected subgraphs of a network, known as components. A component is a set of nodes where a path exists between every pair of nodes. A component is a maximal connected subgraph, where all nodes within it are reachable from each other, and it is not connected to any other nodes. A component can be as simple as a long line of connected nodes with no triangles or k-stars. A path is a fundamental concept that describes a sequence of connections between nodes. It is the route one can follow to travel from one node to another. Paths are essential for understanding properties like the shortest distance between any pair of nodes. A special type of path is a cycle, which is a closed path with no repeated nodes or edges other than the start and end nodes. A cycle has a minimum of three links (e.g., a triangle). From the network science perspective, geometric structures like squares, pentagons, or decagons can all be seen as cycles. The four types of configurations in a network are depicted in Figure 2.

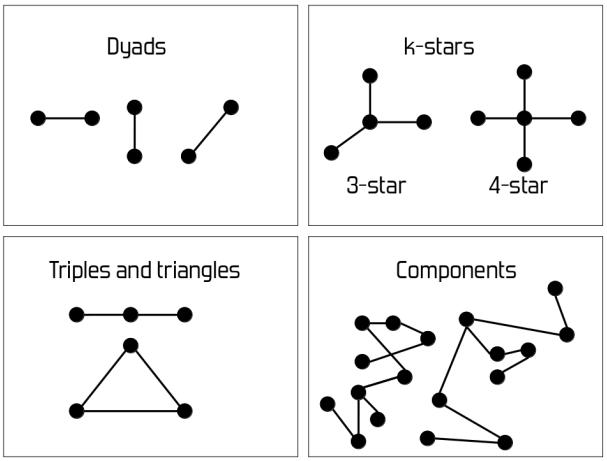


**Fig. 2** Basic configurations in a network: dyads (top left), k-stars (top right), triples and triangles (bottom left), and components (bottom right).

# 3 This is an example for first level head—section head

## 3.1 This is an example for second level head—subsection head

### 3.1.1 This is an example for third level head—subsubsection head

Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text.

**Table 1** Caption text

| temperature | pressure |
|---|---|
| 0 | 0.0002 |
| 20 | 0.0012 |
| 40 | 0.0060 |
| 60 | 0.0300 |
| 80 | 0.0900 |
| 100 | 0.2700 |

# 4 Equations

Equations in LaTeX can either be inline or on-a-line by itself ("display equations"). For inline equations use the `$...$` commands. E.g.: The equation $H\psi = E\psi$ is written via the command `$H \psi = E \psi$`.

For display equations (with auto generated equation numbers) one can use the equation or align environments:

$$\|\tilde{X}(k)\|^2 \leq \frac{\sum_{i=1}^{p} \left\|\tilde{Y}_i(k)\right\|^2 + \sum_{j=1}^{q} \left\|\tilde{Z}_j(k)\right\|^2}{p+q}. \tag{1}$$

where,

$$\begin{aligned} D_\mu &= \partial_\mu - ig\frac{\lambda^a}{2}A_\mu^a \\ F_{\mu\nu}^a &= \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^a \end{aligned} \tag{2}$$

Notice the use of `\nonumber` in the align environment at the end of each line, except the last, so as not to produce equation numbers on lines where no equation numbers are required. The `\label{}` command should only be used at the last line of an align environment where `\nonumber` is not used.

$$Y_\infty = \left(\frac{m}{\text{GeV}}\right)^{-3}\left[1 + \frac{3\ln(m/\text{GeV})}{15} + \frac{\ln(c_2/5)}{15}\right] \tag{3}$$

The class file also supports the use of `\mathbb{}`, `\mathscr{}` and `\mathcal{}` commands. As such `\mathbb{R}`, `\mathscr{R}` and `\mathcal{R}` produces $\mathbb{R}$, $\mathscr{R}$ and $\mathcal{R}$ respectively (refer Subsubsection 3.1.1).

# 5 Tables

Tables can be inserted via the normal `knitr::kable()` function or other table-generating packages.

Tables can also be inserted via the normal table and tabular environment. To put footnotes inside tables you should use `\footnotetext[]{...}` tag. The footnote appears just below the table itself (refer Tables~2 and 3). For the corresponding footnotemark use `\footnotemark[...]`
The input format for the above table is as follows:

**Table 2** Caption text

| Column 1 | Column 2 | Column 3 | Column 4 |
|---|---|---|---|
| row 1 | data 1 | data 2 | data 3 |
| row 2 | data 4 | data 5[1] | data 6 |
| row 3 | data 7 | data 8 | data 9[2] |

Source: This is an example of table footnote. This is an example of table footnote.

[1]Example for a first table footnote. This is an example of table footnote.

[2]Example for a second table footnote. This is an example of table footnote.

```
\begin{table}[<placement-specifier>]
\caption{<table-caption>}\label{<table-label>}%
\begin{tabular}{@{}llll@{}}
\toprule
Column 1 & Column 2 & Column 3 & Column 4\\
\midrule
row 1 & data 1 & data 2  & data 3 \\
row 2 & data 4 & data 5\footnotemark[1] & data 6 \\
row 3 & data 7 & data 8  & data 9\footnotemark[2]\\
\botrule
\end{tabular}
\footnotetext{Source: This is an example of table footnote.
This is an example of table footnote.}
\footnotetext[1]{Example for a first table footnote.
This is an example of table footnote.}
\footnotetext[2]{Example for a second table footnote.
This is an example of table footnote.}
\end{table}
```

**Table 3** Example of a lengthy table which is set to full textwidth

| | Element 1[1] | | | Element 2[2] | | |
|---|---|---|---|---|---|---|
| Project | Energy | $\sigma_{calc}$ | $\sigma_{expt}$ | Energy | $\sigma_{calc}$ | $\sigma_{expt}$ |
| Element 3 | 990 A | 1168 | $1547 \pm 12$ | 780 A | 1166 | $1239 \pm 100$ |
| Element 4 | 500 A | 961 | $922 \pm 10$ | 900 A | 1268 | $1092 \pm 40$ |

Note: This is an example of table footnote. This is an example of table footnote this is an example of table footnote this is an example of table footnote this is an example of table footnote.

[1]Example for a first table footnote.

[2]Example for a second table footnote.

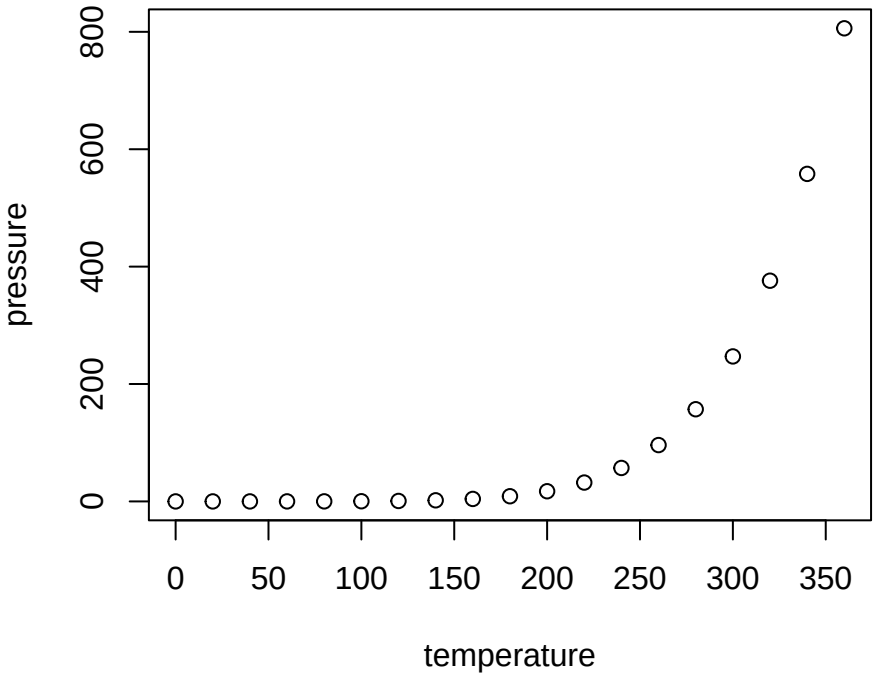


**Fig. 3** This is an example of a caption

In case of double column layout, tables which do not fit in single column width should be set to full text width. For this, you need to use `\begin{table*} ... \end{table*}` instead of `\begin{table} ... \end{table}` environment. Lengthy tables which do not fit in textwidth should be set as rotated table. For this, you need to use `\begin{sidewaystable} ... \end{sidewaystable}` instead of `\begin{table*} ... \end{table*}` environment. This environment puts tables rotated to single column width. For tables rotated to double column width, use `\begin{sidewaystable*} ... \end{sidewaystable*}`.

# 6 Figures

As per the LaTeX standards you need to use eps images for LaTeX compilation and `pdf/jpg/png` images for `PDFLaTeX` compilation. Use the `dev` knitr option to use the approrpate format. This is one of the major difference between LaTeX and `PDFLaTeX`. Each image should be from a single input .eps/vector image file. Avoid using subfigures. The command for inserting images for LaTeX and `PDFLaTeX` can be generalized. The package used to insert images in `LaTeX/PDFLaTeX` is the graphicx package. Figures can be inserted via the normal figure environment as shown in the below example:

**Table 4** Tables which are too long to fit, should be written using the "sidewaystable" environment as shown here

| | Element 1[1] | | | Element[2] | | |
|---|---|---|---|---|---|---|
| Projectile | Energy | $\sigma_{calc}$ | $\sigma_{expt}$ | Energy | $\sigma_{calc}$ | $\sigma_{expt}$ |
| Element 3 | 990 A | 1168 | $1547 \pm 12$ | 780 A | 1166 | $1239 \pm 100$ |
| Element 4 | 500 A | 961 | $922 \pm 10$ | 900 A | 1268 | $1092 \pm 40$ |
| Element 5 | 990 A | 1168 | $1547 \pm 12$ | 780 A | 1166 | $1239 \pm 100$ |
| Element 6 | 500 A | 961 | $922 \pm 10$ | 900 A | 1268 | $1092 \pm 40$ |

Note: This is an example of table footnote this is an example of table footnote this is an example of table footnote this is an example of table footnote this is an example of table footnote.

[1]This is an example of table footnote.

# 7 Algorithms, Program codes and Listings

Packages `algorithm`, `algorithmicx` and `algpseudocode` are used for setting algorithms in LaTeX using the format:

```
\begin{algorithm}
\caption{<alg-caption>}\label{<alg-label>}
\begin{algorithmic}[1]
. . .
\end{algorithmic}
\end{algorithm}
```

You may refer above listed package documentations for more details before setting `algorithm` environment. For program codes, the "program" package is required and the command to be used is `\begin{program} ... \end{program}`. A fast exponentiation procedure:

Similarly, for `listings`, use the `listings` package. `\begin{lstlisting} ... \end{lstlisting}` is used to set environments similar to `verbatim` environment. Refer to the `lstlisting` package documentation for more details.

A fast exponentiation procedure:

```
begin
  for i := 1 to 10 step 1 do
      expt(2, i);
      newline() od                    Comments will be set flush to the right margin
where
proc expt(x, n) ≡
  z := 1;
  do if n = 0 then exit fi;
     do if odd(n) then exit fi;
        comment: This is a comment statement;
        n := n/2; x := x * x od;
     { n > 0 };
     n := n − 1; z := z * x od;
  print(z).
end
```

```
for i:=maxint to 0 do begin \{ do nothing \} end; Write('Case
insensitive'); Write('Pascal keywords.');
```

# 8 Cross referencing

Figures and tables are labeled with a prefix (fig or tab, respectively) plus the chunk label. Other environments such as equation and align can be labelled via the `\label{#label}` command inside or just below the `\caption{}` command. You can then use the label for cross-reference. As an example, consider the chunk label declared for Figure 3 which is fig1. To cross-reference it, use the command `Figure \ref{fig:fig1}`, for which it comes up as "Figure 3".

**Algorithm 1** Calculate $y = x^n$

**Require:** $n \geq 0 \vee x \neq 0$
**Ensure:** $y = x^n$
1: $y \Leftarrow 1$
2: **if** $n < 0$ **then**
3: $X \Leftarrow 1/x$
4: $N \Leftarrow -n$
5: **else**
6: $X \Leftarrow x$
7: $N \Leftarrow n$
8: **end if**
9: **while** $N \neq 0$ **do**
10: **if** $N$ is even **then**
11: $X \Leftarrow X \times X$
12: $N \Leftarrow N/2$
13: **else**[$N$ is odd]
14: $y \Leftarrow y \times X$
15: $N \Leftarrow N - 1$
16: **end if**
17: **end while**

To reference line numbers in an algorithm, consider the label declared for the line number 2 of Algorithm 1 is `\label{algln2}`. To cross-reference it, use the command `\ref{algln2}` for which it comes up as line 2 of Algorithm 1.

### 8.1 Details on reference citations

For citations of references, use **?** or (**?**).

## 9 Examples for theorem like environments

The documentclass for springer `sn-jnl.cls` contains 3 styling that you can use to set new default for theorems and proofs type

*`thmstyleone`* Numbered, theorem head in bold font and theorem text in italic style
*`thmstyletwo`* Numbered, theorem head in roman font and theorem text in italic style
*`thmstylethree`* Numbered, theorem head in bold font and theorem text in roman style

For mathematics journals, theorem styles can be included as shown in the following examples.

**Theorem 1.** *Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text.*

To add labels and subheadings, use LaTeX notation

**Theorem 2** (Theorem subhead)**.** *Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text. Example theorem text.*

Other environments are proposition, example, remark, definition, proof and quote

Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text.

**Proposition 3.** *Example proposition text. Example proposition text. Example proposition text. Example proposition text. Example proposition text. Example proposition text. Example proposition text. Example proposition text. Example proposition text. Example proposition text.*

Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text.

*Example* 1. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem.

Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text.

*Remark* 1. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo. Maecenas lacinia. Nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem.

Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text.

**Definition 1** (Definition sub head)**.** Example definition text. Example definition text. Example definition text. Example definition text. Example definition text. Example definition text. Example definition text. Example definition text.

Additionally a predefined "proof" environment is available. This prints a "Proof" head in italic font style and the "body text" in roman font style with an open square at the end of each proof environment.

*Proof.* Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. Example for proof text. □

Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text. Sample body text.

# 10 Methods

Topical subheadings are allowed. Authors must ensure that their Methods section includes adequate experimental and characterization data necessary for others in the field to reproduce their work. Authors are encouraged to include RIIDs where appropriate.

**Ethical approval declarations** (only required where applicable) Any article reporting experiment/s carried out on (i)˜live vertebrate (or higher invertebrates), (ii)˜humans or (iii)˜human samples must include an unambiguous statement within the methods section that meets the following requirements:

1. Approval: a statement which confirms that all experimental protocols were approved by a named institutional and/or licensing committee. Please identify the approving body in the methods section
2. Accordance: a statement explicitly saying that the methods were carried out in accordance with the relevant guidelines and regulations
3. Informed consent (for experiments involving humans or human tissue samples): include a statement confirming that informed consent was obtained from all participants and/or their legal guardian/s

If your manuscript includes potentially identifying patient/participant information, or if it describes human transplantation research, or if it reports results of a clinical trial then additional information will be required. Please visit (https://www.nature.com/nature-research/editorial-policies) for Nature Portfolio journals, (https://www.springer.com/gp/authors-editors/journal-author/journal-author-helpdesk/publishing-ethics/14214) for Springer Nature journals, or (https://www.biomedcentral.com/getpublished/editorial-policies\#ethics+and+consent) for BMC.

# 11 Discussion

Discussions should be brief and focused. In some disciplines use of Discussion or 'Conclusion' is interchangeable. It is not mandatory to use both. Some journals prefer a section 'Results and Discussion' followed by a section 'Conclusion'. Please refer to Journal-level guidance for any specific requirements.

# 12 Conclusion

Conclusions may be used to restate your hypothesis or research question, restate your major findings, explain the relevance and the added value of your work, highlight any limitations of your study, describe future directions for research and recommendations.

In some disciplines use of Discussion or 'Conclusion' is interchangeable. It is not mandatory to use both. Please refer to Journal-level guidance for any specific requirements.

**Supplementary information.** If your article has accompanying supplementary file/s please state so here.

Authors reporting data from electrophoretic gels and blots should supply the full unprocessed scans for key as part of their Supplementary information. This may be requested by the editorial team/s if it is missing.

Please refer to Journal-level guidance for any specific requirements.

**Acknowledgments.** Acknowledgments are not compulsory. Where included they should be brief. Grant or contribution numbers may be acknowledged.

Please refer to Journal-level guidance for any specific requirements.

## Declarations

Some journals require declarations to be submitted in a standardised format. Please check the Instructions for Authors of the journal to which you are submitting to see if you need to complete this section. If yes, your manuscript must contain the following sections under the heading 'Declarations':

- Funding
- Conflict of interest/Competing interests (check journal-specific guidelines for which heading to use)
- Ethics approval
- Consent to participate
- Consent for publication
- Availability of data and materials
- Code availability
- Authors' contributions

If any of the sections are not relevant to your manuscript, please include the heading and write 'Not applicable' for that section.
Editorial Policies for:
Springer journals and proceedings: https://www.springer.com/gp/editorial-policies
Nature Portfolio journals: https://www.nature.com/nature-research/editorial-policies
*Scientific Reports*: https://www.nature.com/srep/journal-policies/editorial-policies
BMC journals: https://www.biomedcentral.com/getpublished/editorial-policies

## Appendix A Section title of first appendix

An appendix contains supplementary information that is not an essential part of the text itself but which may be helpful in providing a more comprehensive understanding of the research problem or it is information that is too cumbersome to be included in the body of the paper.

For submissions to Nature Portfolio Journals please use the heading "Extended Data".

## References

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