Further LaTeX examples

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1 The align environment and multi-line displayed equations

In our work we will often want to have a sequence of equations where we show the manipulation, perhaps with justifications, of some expression. In such situations we can display this well with the use of an `align` environment. The \\ characters will end the current line and the non-printing alignment character `&` will serve to horizontally align the equations, which we normally do at the equals sign.

Here is an example showing the expansion of a polynomial:

$$\begin{align}
(x+y)^3 &= (x+y)(x+y)^2, \text{ separating one of the factors} \tag{1}\\
&= (x+y)(x^2+2xy+y^2), \text{ multiplying out the square bracket} \tag{2}\\
&= x^3+2x^2y+xy^2+yx^2+2xy^2+y^3, \text{multiplying out the brackets} \tag{3}\\
&= x^3+3x^2y+3xy^2+y^3, \text{ collecting like terms.} \tag{4}
\end{align}$$

Note that the `align` environment automatically attached a numerical label to each equation. If we want to suppress this labeling in all the equations we can use the *starred* version of the environment, as follows,

$$\begin{align*}
(x+y)^3 &= (x+y)(x+y)^2, \text{ separating one of the factors,}\\
&= (x+y)(x^2+2xy+y^2), \text{ multiplying out the square bracket,}\\
&= x^3+2x^2y+xy^2+yx^2+2xy^2+y^3, \text{multiplying out the brackets,}\\
&= x^3+3x^2y+3xy^2+y^3, \text{ collecting like terms.}
\end{align*}$$

Note the use of punctuation to maintain a coherent sentence structure.

2 Importing images/plots and the figure environment

In figure 1 we see a painting of Euclid, by Ribera (1630-1635), image courtesy of Digital image courtesy of the Getty's Open Content Program.

Note that LaTeX will make its own decisions, following various publishing conventions, about where exactly to place the figure. We refer to the figure in our text with the use of a cross-reference.

Figure 1: Euclid by Jusepe de Ribera

3 Crossing-referencing and bibliographic references

Just after any line in the source that creates a label we can put a `\label{..}` command to create a cross-referencing label. Then anywhere in the source where we have a corresponding `\ref{...}` command with the same label as the argument, this will be replaced by the numerical label used on the page. See the example above where I have referred to the painting of Euclid.

4 Typesetting matrices

An example of a typeset 3×3 matrix in math-mode is given here, consider the matrix A defined by

$$A = \begin{pmatrix} 0.5 & 2 & -1 \\ 0 & 0 & 1 \\ 5 & -3 & 0 \end{pmatrix}.$$

The `pmatrix` environment typesets a matrix using parentheses, which is the usual convention. Some authors will use square brackets, typeset using the `bmatrix` environment, as in

$$A = \begin{bmatrix} 0.5 & 2 & -1 \\ 0 & 0 & 1 \\ 5 & -3 & 0 \end{bmatrix}.$$

Determinants can be shown using vertical bars around the matrix, using the `vmatrix` environment, as in

$$\det(A) = \begin{vmatrix} 0.5 & 2 & -1 \\ 0 & 0 & 1 \\ 5 & -3 & 0 \end{vmatrix}.$$

Other variations on the `?matrix` environment are shown at `https://www.overleaf.com/learn/latex/Matrices`.

5 Fine tuning the spacing in math mode

Most of the time LaTeX handles the spacing between elements in math-mode automatically and well. We simply type the sequence of symbols we want in the source. But sometimes we may want to add or subtract a little extra space between characters. Consider the following two equations that give a set definition of the positive reals P,

$$P = \{x \in \mathbb{R}|x > 0\},$$

and

$$P = \{x \in \mathbb{R} \,|\, x > 0\}.$$

Which looks better? I think the second does.

The extra small spaces before and after the | symbol were introduced using the `\,` command. A collection of similar spacing commands can be found at `https://www.overleaf.com/learn/latex/Spacing_in_math_mode`. However, such adjustments are mostly not needed and should be used sparingly. In general, it is best to stick with the default layout.

6 Further work

To continue practice with LaTeX you could

- continue to work with the LaTeX guide from lab session this week,
- work on typesetting a solution to the Mersenne prime exponent problem posed in this week's lab,
- work through the mathematical typesetting challenges, created by Jason Gross, then of MIT. These are shown on the following pages.

References

Ribera, Jusepe de (1630-1635). *Euclid.* The J. Paul Getty Museum, Los Angeles.

$\LaTeX$ Exercises

Jason Gross

$\TeX$ed on September 6, 2010

If you have trouble figuring out how to typeset one of the following, try to figure it out using the Internet before asking me how to typeset it. Knowing how to find the information you want on the Internet is an important skill. If you're stuck or frustrated, feel free to ask for help.

Note that `http://detexify.kirelabs.org/classify.html` is useful.

1 Easy

$$\text{Please type me! The quick brown fox jumps over the lazy dog.} \tag{1}$$

$$e^{i\pi} + 1 = 0 \tag{2}$$

$$e^{i\theta} = \cos\theta + i\sin\theta \tag{3}$$

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{4}$$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{5}$$

$$\vec{L} = \vec{r} \times \vec{p} \tag{6}$$

$$\sqrt[3]{2} \tag{7}$$

$$(x+y)^n = \sum_{r=0}^{n} \binom{n}{r} x^r y^{n-r} \tag{8}$$

$$\sqrt{\frac{a_1^2 + \cdots + a_n^2}{n}} \geq \frac{a_1 + \cdots + a_n}{n} \geq \sqrt[n]{a_1 \cdots a_n} \geq \frac{n}{\frac{1}{a_1} + \cdots + \frac{1}{a_n}} \tag{9}$$

$$|\langle x, y\rangle|^2 \leq \langle x, x\rangle \cdot \langle y, y\rangle \tag{10}$$

$$\begin{aligned}
&\text{A1: } \varphi \longrightarrow (\psi \to \varphi)\\
&\text{A2: } (\varphi \to (\psi \to \theta)) \longrightarrow ((\varphi \to \psi) \to (\varphi \to \theta))\\
&\text{A3: } (\neg\varphi \to \neg\psi) \longrightarrow (\psi \to \varphi)
\end{aligned} \tag{11}$$

2 Medium

$$1_A = \begin{cases} 1 & \text{if } x \in A \\ 0 & \text{if } x \notin A \end{cases} \tag{12}$$

$$n \underbrace{\uparrow \cdots \uparrow}_{n} n = n \to n \to n \tag{13}$$

In the following, note the spacing between the = and the ${}^{1}1$, ${}^{2}2$, and ${}^{{}^{3}3}3$.

$$\begin{aligned} 1 \uparrow 1 &= {}^{1}1 = 1 \\ 2 \uparrow\uparrow 2 &= {}^{2}2 = 4 \\ 3 \uparrow\uparrow\uparrow 3 &= {}^{{}^{3}3}3 = 3 \uparrow\uparrow 3 \uparrow\uparrow 3 = \underbrace{3^{3^{3^{3^{3^{3^{3^{\cdot^{\cdot^{\cdot^{3}}}}}}}}}}}_{3^{3^{3}} \text{ threes}} \end{aligned} \tag{14}$$

$$\frac{\mathrm{d}}{\mathrm{d}x} f(x) = \lim_{\Delta x \to 0} \frac{f(x + \Delta x) - f(x)}{\Delta x} \tag{15}$$

$$\mathrm{H_2O}(\ell) + \mathrm{H_2O}(\ell) \rightleftharpoons \mathrm{H_3O^+}(aq) + \mathrm{OH^-}(aq) \tag{16}$$

$$\Gamma(n+1) \stackrel{\text{def}}{=} \int_0^\infty e^{-t} t^n \mathrm{d}t \tag{17}$$

$$\gcd(n, m \bmod n); \quad x \equiv y \pmod b; \quad x \equiv y \mod c; \quad x \equiv y \pod d \tag{18}$$

In the following, note the bold symbols.

$$\begin{aligned} \nabla \cdot \mathbf{E} &= \frac{\rho}{\varepsilon_0} \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{B} &= \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \end{aligned} \tag{19}$$

For the following exercise, you will need to `\usepackage{esint}` to get the symbol $\oiint$.

$$\begin{aligned} \oiint_{\partial V} \mathbf{E} \cdot \mathrm{d}\mathbf{A} &= \frac{Q(V)}{\varepsilon_0} \\ \oiint_{\partial V} \mathbf{B} \cdot \mathrm{d}\mathbf{A} &= 0 \\ \oint_{\partial S} \mathbf{E} \cdot \mathrm{d}\mathbf{l} &= -\frac{\partial \Phi_{B,S}}{\partial t} \\ \oint_{\partial S} \mathbf{B} \cdot \mathrm{d}\mathbf{l} &= \mu_0 I_S + \mu_0 \varepsilon_0 \frac{\partial \Phi_{E,S}}{\partial t} \end{aligned} \tag{20}$$

You might find the environments `bmatrix` and `pmatrix` useful for the following exercises.

$$\rho_\theta = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \tag{21}$$

$$\left[\begin{array}{c|ccc} 1 & 0 & \cdots & 0 \\ \hline 0 & * & \cdots & * \\ \vdots & \vdots & \ddots & \vdots \\ 0 & * & \cdots & * \end{array}\right] = \begin{array}{|c|ccc|} \hline 1 & 0 & \cdots & 0 \\ \hline 0 & * & \cdots & * \\ \vdots & \vdots & \ddots & \vdots \\ 0 & * & \cdots & * \\ \hline \end{array} \tag{22}$$

Note the locations of the bounds on the summation in the following exercise.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N} p_i(x_i - \bar{x})^2} = \sqrt{\frac{\displaystyle\sum_{i=1}^{N} p_i(x_i - \bar{x})^2}{N}} \tag{23}$$

$$\varphi(n) = n \cdot \prod_{\substack{p \mid n \\ p \text{ prime}}} \left(1 - \frac{1}{p}\right) \tag{24}$$

If you `\usepackage{mathtools}`, you can make it look like

$$\varphi(n) = n \cdot \prod_{\substack{p \mid n \\ p \text{ prime}}} \left(1 - \frac{1}{p}\right) \tag{25}$$

$${}^{4}_{12}\mathrm{C}^{5+}_{2} \quad {}^{14}_{2}\mathrm{C}^{5+}_{2} \quad {}^{4}_{12}\mathrm{C}^{5+}_{2} \quad {}^{14}\mathrm{C}^{5+}_{2} \quad {}_{2}\mathrm{C}^{5+}_{2} \tag{26}$$

In the following, note the size of the /, and the spacing on the sides of the |.

$$\mathbb{Q} \cong \left\{ \frac{a}{b} \;\middle|\; a, b \in \mathbb{Z} \text{ and } b \neq 0 \right\} \Big/ \sim$$

$$\frac{a}{b} \sim \frac{c}{d} \iff ad - bc = 0 \tag{27}$$

Notice both the horizontal and vertical spacing in the following exercise.

$$\begin{aligned} 1 \uparrow 1 &= {}^{1}1 = 1 \\ 2 \uparrow\uparrow 2 &= {}^{2}2 = 4 \\ 3 \uparrow\uparrow\uparrow 3 &= {}^{3^{3}}3 = 3 \uparrow\uparrow 3 \uparrow\uparrow 3 = \underbrace{3^{3^{3^{3^{3^{3^{\cdot^{\cdot^{\cdot^{3}}}}}}}}}}_{3^{3^{3}} \text{ threes}} \end{aligned} \tag{28}$$

3 Hard

The command `\newcommand{\`*name*`}[`*n*`][`*default*`]{`*definition*`}` defines a new command, where n is the number of parameters and *default* is the default value for the first parameter. Parameters in braces ({ }) are required, and parameters in square brackets ([ ]) are optional. The parameters can be referred to via `#1`, `#2`, ..., `#9`. Using `\newcommand{\mathset}[2][`*default value for the first argument*`]{`*command definition*`}`, define a command `\mathset` that acts as follows. Notice, in particular, the sizes of the middle bar, the sizes of the braces, and the spacing between the middle bar and the things on each side.

`\mathset{1}`	gives $\{1\}$
`\mathset[x]{0\leq x\leq 1}`	gives $\{x \,\|\, 0 \leq x \leq 1\}$
`\mathset[(x)_i]{`$\sum_i x_i \in A$`}`	gives $\left\{ (x)_i \,\middle\|\, \sum_i x_i \in A \right\}$
`\mathset[`$\sum_{i=1}^{\infty} n^{-s}$`]{n \in A}`	gives $\left\{ \sum_{i=1}^{\infty} n^{-s} \,\middle\|\, n \in A \right\}$
`\mathset{}`	gives $\emptyset$
`\mathset[`$\frac{1}{1+\frac{1}{x}}$`]{x\in A}`	gives $\left\{ \frac{1}{1+\frac{1}{x}} \,\middle\|\, x \in A \right\}$
`\mathset[`$\frac{1}{1+\frac{1}{1+\frac{1}{x}}}$`]{x\in A}`	gives $\left\{ \frac{1}{1+\frac{1}{1+\frac{1}{x}}} \,\middle\|\, x \in A \right\}$
`\mathset[`$\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{x}}}}$`]{x\in A}`	gives $\left\{ 1 + \frac{1}{\frac{1}{1+\frac{1}{1+\frac{1}{x}}}} \,\middle\|\, x \in A \right\}$
`\mathset[`$\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{x}}}}}$`]{x\in A}`	gives $\left\{ \frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{x}}}}} \,\middle\|\, x \in A \right\}$
`\mathset[`$\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{x}}}}}}$`]{x\in A}`	gives $\left\{ \frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{x}}}}}} \,\middle\|\, x \in A \right\}$
`\mathset[`$\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{x}}}}}}}$`]{x\in A}`	gives $\left\{ \frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{1+\frac{1}{x}}}}}}} \,\middle\|\, x \in A \right\}$

4 Insane

Write a command `\outputcode` which outputs the code of the document being typeset.

The following exercise idea is taken from the TeXbook. Define a command `\primes{`n`}` which typesets the first n primes. For example, `\primes{30}` should give 2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97, 101, 103, 107, 109, and 113.

5 Diabolical

The Ackermann function is defined as

$$A(m,n) = \begin{cases} n+1 & \text{if } m = 0 \\ A(m-1,1) & \text{if } m > 0 \text{ and } n = 0 \\ A(m-1, A(m, n-1)) & \text{if } m > 0 \text{ and } n > 0 \end{cases}$$

Define a command, `\ackermann{`m`}{`n`}`, which computes the Ackermann function and displays the intermediate values. For an extra challenge, ensure that it only displays each sub-value only once (per command call; a second call to `\ackermann{`m`}{`n`}` should typeset the same thing as the first one).

For example, `\ackermann{2}{2}` should display

$$\begin{aligned} A(2,2) &= A(1, A(2,1)) \\ &= A(1, A(1, A(2,0))) \\ &= A(1, A(1, A(1,1))) \\ &= A(1, A(1, A(0, A(1,0)))) \\ &= A(1, A(1, A(0, A(0,1)))) \\ &= A(1, A(1, A(0,2))) \\ &= A(1, A(1,3)) \\ &= A(1, A(0, A(1,2))) \\ &= A(1, A(0, A(0, A(1,1)))) \\ &= A(1, A(0, A(0,3))) \\ &= A(1, A(0,4)) \\ &= A(1,5) \\ &= A(0, A(1,4)) \\ &= A(0, A(0, A(1,3))) \\ &= A(0, A(0,5)) \\ &= A(0,6) \\ &= 7 \end{aligned}$$

References

Ribera, Jusepe de (1630-1635). *Euclid*. The J. Paul Getty Museum, Los Angeles.