# Eigenmath Manual

9634295@gmail.com



Commands are entered here

Multiple commands can be put together in a script. Scripts are run by clicking the Run button. After a script runs, all of the results are available in command mode. To export a result, click on the result text. The result can now be printed with HP or copied to the pasteboard with HC. (Note that it is necessary to click on the result text instead of somewhere else in the result window.)

Note: Times New Roman and Times New Roman Italic fonts need to be the standard Mac fonts that include special symbols and Greek letters. See the following link for correcting font problems.

support.apple.com/guide/font-book/restore-fonts-that-came-with-your-mac-fb34862/mac

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# 1 Introduction

Consider the canonical commutation relation in one dimension.

$$XP - PX = i\hbar$$

Let

$$X = x, \quad P = -i\hbar\frac{\partial}{\partial x}$$

Show that

$$(XP - PX)\psi(x,t) = i\hbar\psi(x,t)$$

Eigenmath code:

X(f) = x f P(f) = -i hbar d(f,x) X(P(psi(x,t))) - P(X(psi(x,t)))

Result:

 $i\hbar\psi(x,t)$ 

Another example: Let

$$H = \frac{P^2}{2m}$$

Show that

$$XH - HX = \frac{i\hbar P}{m}$$

Eigenmath code:

```
X(f) = x f
P(f) = -i \text{ hbar } d(f,x)
H(f) = P(P(f)) / (2 m)
A = X(H(psi(x,t))) - H(X(psi(x,t)))
B = i \text{ hbar } P(psi(x,t)) / m
check(A == B) -- \text{ continue if } A \text{ equals } B
"ok"
```

Result:

 $\mathbf{ok}$ 

# 2 Syntax

Arithmetic operators have the expected precedence of multiplication and division before addition and subtraction. Subexpressions in parentheses have highest precedence.

Math	Eigenmath	Comment
a = b	a == b	test for equality
-a	-a	negation
a + b	a+b	addition
a-b	a-b	subtraction
ab	a b	$multiplication, \ also \ {\tt a*b}$
$rac{a}{b}$	a/b	division
$\frac{a}{bc}$	a/b/c	division is left-associative
$a^2$	a^2	power
$\sqrt{a}$	sqrt(a)	square root, also a^(1/2)
$a\left(b+c ight)$	a (b+c)	space is required
f(a)	f(a)	function
$\begin{pmatrix} a \\ b \\ c \end{pmatrix}$	(a,b,c)	vector
$\begin{pmatrix} a & b \\ c & d \end{pmatrix}$	((a,b),(c,d))	matrix
$F^1{}_2$	F[1,2]	tensor component access
	"hello, world"	string literal
$\pi$	pi	
e	exp(1)	natural number

Parentheses are required around negative exponents. For example,

10^(-3)

instead of

#### 10^-3

In general, parentheses are always required when the exponent is an expression. For example,  $x^1/2$  is evaluated as  $(x^1)/2$  which is probably not the desired result.

#### x^1/2

 $\frac{1}{2}x$ 

Using  $x^{(1/2)}$  yields the desired result.

#### x^(1/2)

 $x^{1/2}$ 

# 3 Symbols

Symbols are defined with an equals sign.

 $N = 212^{17}$ 

No result is printed when a symbol is defined. To see the value of a symbol, just evaluate it.

N

N=3529471145760275132301897342055866171392

Symbols can have more that one letter. Everything after the first letter is displayed as a subscript.

NA = 6.02214 10<sup>23</sup>

 $N_A = 6.02214 \times 10^{23}$ 

A symbol can be the name of a Greek letter.

xi = 1/2xi  $\xi = \frac{1}{2}$ 

Greek letters can appear in subscripts.

Amu = 2.0 Amu

 $A_{\mu} = 2.0$ 

The following example shows how a symbol is scanned to find Greek letters.

```
alphamunu = 1
alphamunu
```

 $\alpha_{\mu\nu} = 1$ 

Symbol definitions are evaluated serially until a terminal symbol is reached. The following example sets A = B followed by B = C. Then when A is evaluated, the result is C.

 $\begin{array}{rrrr} A & = & B \\ B & = & C \\ A \end{array}$ 

A = C

Although A = C is printed, inside the program the binding of A is still B, as can be seen with the **binding** function.

binding(A)

#### В

The quote function returns its argument unevaluated and can be used to clear a symbol. The following example clears A so that its evaluation goes back to being A instead of C.

```
A = quote(A)
A
```

A

# 4 Units of measure

Symbols can be used for units of measure.

```
v = 1.2 meter / second
v \frac{1.2 m_{eter}}{s_{econd}}
```

Assign strings to unit symbols for improved display appearance.

```
meter = "m"
second = "s"
v
\frac{1.2 \text{ m}}{\text{s}}
```

Derived units can be handled by converting to base units.

```
h = 6.626 10<sup>(-34)</sup> joule second
joule = kilogram meter<sup>2</sup> / second<sup>2</sup>
kilogram = "kg"
h
h = \frac{6.626 \times 10^{-34} \,\mathrm{kg} \,\mathrm{m}^2}{\mathrm{s}}
```

Here is a trick for displaying derived units. In this example, convert joules to string "J".

#### h "J" / joule

 $6.626\times10^{-34}\,\mathrm{J\,s}$ 

See the following link for a script with recommended physical values in SI units.

https://georgeweigt.github.io/examples/physical-constants.html

# 5 Function definitions

The following example defines a sinc function and evaluates it at  $\pi/2$ .

```
f(x) = \sin(x)/x
f(pi/2)
\frac{2}{\pi}
```

In a function definition, use eval to evaluate an argument with a substitution.

```
h(f,a,b) = eval(f,x,b) - eval(f,x,a)
h(x^2, 1, 2)
```

#### 3

To define a local symbol in a function, extend the argument list. In the following example, argument y is used as a local symbol. Note that function L is called without supplying an argument for y.

```
L(f,n,y) = eval(exp(y) d(exp(-y) y^n, y, n) / n!, y, f)
L(cos(x),2)
```

```
\frac{1}{2}\cos(x)^2 - 2\cos(x) + 1
```

Use do when multiple steps are needed in a function. The last do item is the return value. The following example defines function I for integrating hydrogen wavefunctions.

```
I(f) = do(
  f = expform(f r^2 sin(theta)),
  f = defint(f, theta, 0, pi, phi, 0, 2 pi),
  f = integral(f,r),
  -eval(f,r,0) -- return value
)
```

Notes:

- 1. Maximum number of arguments is nine.
- 2. Argument scope is restricted to just the function definition.
- 3. Function definitions cannot be nested.

# 6 Arithmetic

Big integer arithmetic is used so that numerical values can exceed machine size.

#### 2^64

```
18446744073709551616
```

#### 212^17

3529471145760275132301897342055866171392

Rational number arithmetic is used by default.

1/2 + 1/3

# $\frac{5}{6}$

Floating point arithmetic can also be used.

1/2 + 1/3.0

#### 0.833333

The float function converts integers and rationals to floating point values.

#### float(212^17)

 $3.52947\times10^{39}$ 

The following example shows how to enter a floating point value using scientific notation.

epsilon =  $1.0 \ 10^{-6}$ epsilon

 $\varepsilon = 1.0 \times 10^{-6}$ 

# 7 Complex numbers

Symbol i is initialized to  $\sqrt{-1}$ .

Complex quantities can be entered in either rectangular or polar form.

```
a + i b

a + ib

exp(1/3 i pi)

\exp\left(\frac{1}{3}i\pi\right)
```

Converting a complex number to rectangular or polar coordinates causes simplification of mixed forms.

```
A = 1 + i

B = \text{sqrt}(2) \exp(1/4 \text{ i pi})

A - B

1 + i - 2^{1/2} \exp\left(\frac{1}{4}i\pi\right)

\text{rect(last)}
```

0

Rectangular complex quantities, when raised to a power, are multiplied out.

 $(a + i b)^2$  $a^2 - b^2 + 2iab$ 

When a and b are numerical and the power is negative, the evaluation is done as follows.

$$(a+ib)^{-n} = \left(\frac{a-ib}{(a+ib)(a-ib)}\right)^n = \left(\frac{a-ib}{a^2+b^2}\right)^n$$

Here are a few examples.

1/(2 - i) $\frac{2}{5} + \frac{1}{5}i$ (-1 + 3 i)/(2 - i)-1 + i

The absolute value of a complex number returns its magnitude.

```
abs(3 + 4 i)
5
```

The imaginary unit can be changed from i to j by defining  $j = \sqrt{-1}$ .

```
j = sqrt(-1)
sqrt(-4)
```

```
2j
```

### 8 Draw

draw(f,x) draws a graph of function f of x.

 $draw(x^2,x)$ 



The vectors **xrange** and **yrange** control the scale of the graph.

```
xrange = (-1,1)
yrange = (0,2)
draw(x<sup>2</sup>)
```



Parametric drawing occurs when a function returns a vector. The vector trange controls the parametric range. The default is trange=(-pi,pi). In the following example, draw varies theta over the default range  $-\pi$  to  $+\pi$ .

```
xrange = (-10,10)
yrange = (-10,10)
f = 5 (cos(theta),sin(theta))
draw(f,theta)
```



In the following example, trange is reduced to draw a quarter circle instead of a full circle.

```
trange = (0,pi/2)
f = 5 (cos(theta),sin(theta))
draw(f,theta)
```



Draw a lemniscate.

```
trange = (-pi,pi)
X = cos(t) / (1 + sin(t)^2)
Y = sin(t) cos(t) / (1 + sin(t)^2)
f = 5 (X,Y)
draw(f,t)
```



Draw a cardioid.

```
r = (1 + cos(t)) / 2
u = (cos(t),sin(t))
f = r u
xrange = (-1,1)
yrange = (-1,1)
trange = (0,2pi)
draw(f,t)
```



### 9 Linear algebra

dot(a,b,...) returns the inner product of vectors, matrices, and higher rank tensors. Also known as the matrix product. Arguments are evaluated from right to left for maximum efficiency when the rightmost argument is a vector.

Example 1. Compute the product AX for

$$A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}, \quad X = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$$

```
A = ((a11,a12),(a21,a22))
X = (x1,x2)
dot(A,X)
```

```
\begin{bmatrix} a_{11}x_1 + a_{12}x_2 \\ a_{21}x_1 + a_{22}x_2 \end{bmatrix}
```

Example 2. Solve for vector X in AX = B.

```
A = ((3,7), (1,-9))

B = (16,-22)

X = dot(inv(A),B)

X

X = \begin{bmatrix} -\frac{5}{17} \\ \frac{41}{17} \end{bmatrix}
```

Example 3. Show that

$$A^{-1} = \frac{\operatorname{adj} A}{\det A}$$

A = ((a,b),(c,d))
inv(A) == adj(A) / det(A)
1

# 10 Component arithmetic

Tensor plus scalar adds scalar to each tensor component.

```
A = ((a,b), (c,d))
A + 10
\begin{bmatrix} a+10 & b+10 \\ c+10 & d+10 \end{bmatrix}
```

The product of two tensors is the Hadamard (element-wise) product.

$$A = ((a,b),(c,d))$$
$$A A$$
$$\begin{bmatrix} a^2 & b^2 \\ c^2 & d^2 \end{bmatrix}$$

Tensor raised to a power raises each component to the power.

$$A = ((a,b),(c,d))$$

$$A^{2}$$

$$\begin{bmatrix} a^{2} & b^{2} \\ c^{2} & d^{2} \end{bmatrix}$$

### 11 Quantum computing

A quantum computer can be simulated by applying rotations to a unit vector  $u \in \mathbb{C}^{2^n}$  where  $\mathbb{C}$  is the set of complex numbers and n is the number of qubits. The dimension is  $2^n$  because a register with n qubits has  $2^n$  eigenstates. (Recall that an eigenstate is the output of a quantum computer.) Quantum operations are "rotations" because they preserve |u| = 1. Mathematically, a rotation of u is equivalent to the product Ru where R is a  $2^n \times 2^n$  matrix.

Eigenstates  $|j\rangle$  are represented by the following vectors. (Each vector has  $2^n$  elements.)

$$|0\rangle = (1, 0, 0, \dots, 0)$$
  

$$|1\rangle = (0, 1, 0, \dots, 0)$$
  

$$|2\rangle = (0, 0, 1, \dots, 0)$$
  

$$\vdots$$
  

$$|2^{n} - 1\rangle = (0, 0, 0, \dots, 1)$$

A quantum computer algorithm is a sequence of rotations applied to the initial state  $|0\rangle$ . (The sequence could be combined into a single rotation by associativity of matrix multiplication.) Let  $\psi_f$  be the final state of the quantum computer after all the rotations have been applied. Like any other state,  $\psi_f$  is a linear combination of eigenstates.

$$\psi_f = \sum_{j=0}^{2^n-1} c_j |j\rangle, \quad c_j \in \mathbb{C}, \quad |\psi_f| = 1$$

The last step is to measure  $\psi_f$  and get a result. Measurement rotates  $\psi_f$  to an eigenstate  $|j\rangle$ . The measurement result is  $|j\rangle$ . The probability  $P_j$  of getting a specific result  $|j\rangle$  is

$$P_j = |c_j|^2 = c_j c_j^*$$

Note that if  $\psi_f$  is already an eigenstate then no rotation occurs. (The probability of observing a different eigenstate is zero.) Since the measurement result is always an eigenstate, the coefficients  $c_j$  cannot be observed. However, the same calculation can be run multiple times to obtain a probability distribution of results. The probability distribution is an estimate of  $|c_j|^2$  for each  $|j\rangle$  in  $\psi_f$ .

Unlike a real quantum computer, in a simulation the final state  $\psi_f$ , or any other state, is available for inspection. Hence there is no need to simulate the measurement process. The probability distribution of the result can be computed directly as

$$P = \psi_f \, \psi_f^*$$

where  $\psi_f \psi_f^*$  is the Hadamard (element-wise) product of vector  $\psi_f$  and its complex conjugate. Result P is a vector such that  $P_j$  is the probability of eigenstate  $|j\rangle$  and

$$\sum_{j=0}^{2^{n}-1} P_{j} = 1$$

Note: Eigenmath index numbering begins with 1 hence P[1] is the probability of  $|0\rangle$ , P[2] is the probability of  $|1\rangle$ , etc.

The Eigenmath function rotate(u, s, k, ...) rotates vector u and returns the result. Vector u is required to have  $2^n$  elements where n is an integer from 1 to 15. Arguments s, k, ... are a sequence of rotation codes where s is an upper case letter and k is a qubit number from 0 to n-1. Rotations are evaluated from left to right. The available rotation codes are

C, kControl prefix H, kHadamard  $P, k, \phi$ Phase modifier (use  $\phi = \frac{1}{4}\pi$  for T rotation) Quantum Fourier transform Q, kV, kInverse quantum Fourier transform W, k, jSwap bits X, kPauli X Y, kPauli Y Z, kPauli Z

Control prefix C, k modifies the next rotation code so that it is a controlled rotation with k as the control qubit. Use two or more prefixes to specify multiple control qubits. For example, C, k, C, j, X, m is a Toffoli rotation. Fourier rotations Q, k and V, k are applied to qubits 0 through k. (Q and V ignore any control prefix.)

List of rotate(u, s, k, ...) error codes:

- 1 Argument u is not a vector or does not have  $2^n$  elements where n = 1, 2, ..., 15.
- 2 Unexpected end of argument list (i.e., missing argument).
- 3 Bit number format error or range error.
- 4 Unknown rotation code.

Example: Verify the following truth table for quantum operator CNOT where qubit 0 is the control and qubit 1 is the target. (Target is inverted when control is set.)

rangee	Control	Output		
0	0	00		
0	1	11		
1	0	10		
1	1	01		
,1) CN	NOT, cont	rol O, t	arget 1	
	0 0 1 1 1) CN	0 0 0 1 1 0 1 1 1) CNOT, cont	0 0 00 0 1 11 1 0 10 1 1 01 1) CNOT, control 0, t	0 0 00 0 1 11 1 0 10 1 1 01 1) CNOT, control 0, target 1

ket11 = (0,0,0,1)
U(ket00) == ket00
U(ket01) == ket11
U(ket10) == ket10
U(ket11) == ket01

Here are some useful Eigenmath code snippets for setting up a simulation and computing the result.

```
1. Initialize \psi = |0\rangle.
```

```
n = 4 -- number of qubits (example)
N = 2^n -- number of eigenstates
psi = zero(N)
psi[1] = 1
```

2. Compute the probability distribution for state  $\psi$ .

```
P = psi conj(psi)
```

Hence

 $P[1] = \text{probability that } |0\rangle$  will be the result  $P[2] = \text{probability that } |1\rangle$  will be the result  $P[3] = \text{probability that } |2\rangle$  will be the result :  $P[N] = \text{probability that } |N - 1\rangle$  will be the result

3. (Only for macOS) Draw a probability distribution.

```
xrange = (0,N)
yrange = (0,1)
draw(P[ceiling(x)],x)
```

4. Compute an expectation value.

sum(k,1,N, (k - 1) P[k])

5. Make the high order qubit "don't care."

```
for(k,1,N/2, P[k] = P[k] + P[k + N/2])
```

Hence for N = 16

 $\begin{array}{l} {\sf P[1]} = {\rm probability \ that \ the \ result \ will \ be \ |0\rangle \ or \ |8\rangle} \\ {\sf P[2]} = {\rm probability \ that \ the \ result \ will \ be \ |1\rangle \ or \ |9\rangle} \\ {\sf P[3]} = {\rm probability \ that \ the \ result \ will \ be \ |2\rangle \ or \ |10\rangle} \\ \vdots \\ {\sf P[8]} = {\rm probability \ that \ the \ result \ will \ be \ |7\rangle \ or \ |15\rangle} \end{array}$ 

# 12 Derivative

d(f,x) returns the derivative of f with respect to x.

 $d(x^2,x)$ 

2x

Extend the argument list for multiderivatives.

f = 1 / (x + y)d(f,x,y)  $\frac{2}{(x+y)^3}$ 

d(sin(x),x,x)

 $-\sin(x)$ 

Another syntax for nth derivative.

d(sin(x), x, 2)

 $-\sin(x)$ 

The gradient of f is returned for vector x in d(f,x).

#### $r = sqrt(x^2 + y^2)$ d(r,(x,y))

$$\begin{bmatrix} \frac{x}{(x^2+y^2)^{1/2}} \\ \frac{y}{(x^2+y^2)^{1/2}} \end{bmatrix}$$

The f in d(f,x) can be a vector or higher rank function. Gradient increases rank by one.

```
F = (x^2, y^2)

X = (x, y)

d(F, X)

\begin{bmatrix} 2x & 0 \\ 0 & 2y \end{bmatrix}
```

# **13** Template functions

Function f in d(f,x) does not have to be defined, it can be a template function with just a name and an argument list. The argument list determines the result. For example, d(f(x),x) evaluates to itself because f depends on x. However, d(f(x),y) evaluates to zero because f does not depend on y.

Example 1. f(x) depends on x.

d(f(x),x)

d(f(x), x)

Example 2. f(x) does not depend on y.

d(f(x), y)

0

Example 3. f(x, y) depends on both x and y.

d(f(x,y),y)

d(f(x,y),y)

Example 4. f() is a wildcard that matches any symbol.

d(f(),t)

 $\mathbf{d}(f(),t)$ 

Template functions are useful for working with differential forms. For example, show that

 $\nabla \cdot (\nabla \times \mathbf{F}) = 0$ 

F = (Fx(),Fy(),Fz())
div(curl(F))

0

# 14 Laplacian

The Laplacian  $\nabla^2$  is the divergence of the gradient of scalar function f.

$$\nabla^2 f = \nabla \cdot \nabla f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2}$$

div(grad(f()))

$$d(d(f(), x), x) + d(d(f(), y), y) + d(d(f(), z), z)$$

This is the vector Laplacian.

$$\nabla^{2}\mathbf{A} = \nabla \cdot \nabla \mathbf{A} - \nabla \times (\nabla \times \mathbf{A}) = \begin{pmatrix} \nabla^{2}A_{x} \\ \nabla^{2}A_{y} \\ \nabla^{2}A_{z} \end{pmatrix} = \frac{\partial^{2}\mathbf{A}}{\partial x^{2}} + \frac{\partial^{2}\mathbf{A}}{\partial y^{2}} + \frac{\partial^{2}\mathbf{A}}{\partial z^{2}}$$

A = (Ax(),Ay(),Az())div(grad(A)) - curl(curl(A)) == d(A,x,x) + d(A,y,y) + d(A,z,z)

1

Show that

$$\nabla \cdot \nabla \mathbf{A} = \nabla (\nabla \cdot \mathbf{A})$$

div(grad(A)) == grad(div(A))

1

# 15 Integral

integral(f,x) returns the integral of f with respect to x.

```
integral(x^2,x)
```

```
\frac{1}{3}x^3
```

Extend the argument list for multiple integrals.

```
f = x y
integral(f,x,y)
\frac{1}{4}x^2y^2
```

defint(f,x,a,b) computes the definite integral of f with respect to x evaluated from a to b. The argument list can be extended for multiple integrals. The following example computes the integral of  $f = x^2$  over the domain of a semicircle. For each x along the abscissa, yranges from 0 to  $\sqrt{1-x^2}$ .

```
defint(x<sup>2</sup>, y, 0, sqrt(1 - x<sup>2</sup>), x, -1, 1)
```

```
\frac{1}{8}\pi
```

Alternatively, eval can be used to compute a definite integral step by step.

```
I = integral(x^2,y)
I = eval(I,y,sqrt(1 - x^2)) - eval(I,y,0)
I = integral(I,x)
eval(I,x,1) - eval(I,x,-1)
```

#### $\frac{1}{8}\pi$

Here is a useful trick. Integrals involving sine and cosine can often be solved using exponentials. For example, the definite integral

$$\int_0^{2\pi} \left( \sin^4 t - 2\cos^3(t/2)\sin t \right) dt$$

can be solved as follows.

```
f = sin(t)<sup>4</sup> - 2 cos(t/2)<sup>3</sup> sin(t)
f = expform(f)
defint(f, t, 0, 2 pi)
\frac{3}{4}\pi - \frac{16}{5}
```

# 16 Arc length

Let g(t) be a parametric function that draws a curve in  $\mathbb{R}^n$ . The arc length from g(a) to g(b) is given by

$$\int_a^b |g'(t)|\,dt$$

where |g'(t)| is the length of the tangent vector at g(t).

Example 1. Find the length of the curve  $y = x^2$  from x = 0 to x = 1.

```
g = (t,t^2)
defint(abs(d(g,t)),t,0,1)
\frac{1}{2} 5^{1/2} - \frac{1}{4} \log(2) + \frac{1}{4} \log(2 5^{1/2} + 4)
```

float

1.47894

As expected, the result is greater than  $\sqrt{2} \approx 1.414$ , the length of a straight line from (0,0) to (1,1).

The following script does a discrete computation of the arc length by dividing the curve into 100 pieces.

 $g(t) = (t,t^2)$ h(k) = abs(g(k/100.0) - g((k-1)/100.0)) sum(k,1,100,h(k))

1.47894

As expected, the discrete result matches the analytic result.

Example 2. Find the length of the curve  $y = x^{3/2}$  from the origin to  $x = \frac{4}{3}$ .

 $g = (t,t^{(3/2)})$ defint(abs(d(g,t)),t,0,4/3)

 $\frac{56}{27}$ 

# 17 Line integral

There are two kinds of line integrals, one for scalar fields and one for vector fields. The following table shows how both are based on the calculation of arc length.

	Abstract form	Computable form
Arc length	$\int_C ds$	$\int_{a}^{b}  g'(t)   dt$
Line integral, scalar field	$\int_C f  ds$	$\int_{a}^{b} f(g(t)) \left  g'(t) \right  dt$
Line integral, vector field	$\int_C (F \cdot u)  ds$	$\int_{a}^{b} F(g(t)) \cdot g'(t)  dt$

Note that for the measure ds we have

$$ds = |g'(t)| \, dt$$

For vector fields, symbol u is the unit tangent vector

$$u = \frac{g'(t)}{|g'(t)|}$$

Note that u cancels with ds as follows.

$$\int_{C} (F \cdot u) \, ds = \int_{a}^{b} \left( F(g(t)) \cdot \frac{g'(t)}{|g'(t)|} \right) |g'(t)| \, dt = \int_{a}^{b} F(g(t)) \cdot g'(t) \, dt$$

Example 1. Evaluate  $\int_C x \, ds$  where C is a straight line from (0,0) to (1,1).

x = t y = t g = (x,y) defint(x abs(d(g,t)), t, 0, 1)

 $\frac{1}{2^{1/2}}$ 

Example 2. Evaluate  $\int_C x \, dx$  where C is a straight line from (0,0) to (1,1).

We have  $x \, dx = (F \cdot u) \, ds$  hence

```
x = t
y = t
g = (x,y)
F = (x,0)
defint(dot(F,d(g,t)), t, 0, 1)
<sup>1</sup>/<sub>2</sub>
```

The following line integral problems are from *Advanced Calculus*, *Fifth Edition* by Wilfred Kaplan.

Example 3. Evaluate  $\int y^2 dx$  along the straight line from (0,0) to (2,2).

The following solution parametrizes x and y so that the endpoint (2, 2) corresponds to t = 1.

```
x = 2 t
y = 2 t
g = (x,y)
F = (y<sup>2</sup>,0)
defint(dot(F,d(g,t)), t, 0, 1)
```

 $\frac{8}{3}$ 

Example 4. Evaluate  $\int z \, dx + x \, dy + y \, dz$  along the path x = 2t + 1,  $y = t^2$ ,  $z = 1 + t^3$ ,  $0 \le t \le 1$ .

```
x = 2 t + 1
y = t<sup>2</sup>
z = 1 + t<sup>3</sup>
g = (x,y,z)
F = (z,x,y)
defint(dot(F,d(g,t)), t, 0, 1)
```

 $\frac{163}{30}$ 

### 18 Surface area

Let S be a surface parameterized by x and y. That is, let S = (x, y, z) where z = f(x, y). The tangent lines at a point on S form a tiny parallelogram. The area a of the parallelogram is given by the magnitude of the cross product.

$$a = \left| \frac{\partial S}{\partial x} \times \frac{\partial S}{\partial y} \right|$$

By summing over all the parallelograms we obtain the total surface area A. Hence

$$A = \int \int dA = \int \int a \, dx \, dy$$

The following example computes the surface area of a unit disk parallel to the xy plane.

```
z = 2
S = (x,y,z)
a = abs(cross(d(S,x),d(S,y)))
defint(a,y,-sqrt(1 - x<sup>2</sup>),sqrt(1 - x<sup>2</sup>),x,-1,1)
```

```
\pi
```

The result is  $\pi$ , the area of a unit circle, which is what we expect. The following example computes the surface area of  $z = x^2 + 2y$  over a unit square.

$$z = x^{2} + 2y$$
  

$$S = (x,y,z)$$
  

$$a = abs(cross(d(S,x),d(S,y)))$$
  

$$defint(a,x,0,1,y,0,1)$$
  

$$\frac{5}{8}\log(5) + \frac{3}{2}$$

The following exercise is from *Multivariable Mathematics* by Williamson and Trotter, p. 598. Find the area of the spiral ramp defined by

$$S = \begin{pmatrix} u \cos v \\ u \sin v \\ v \end{pmatrix}, \quad 0 \le u \le 1, \quad 0 \le v \le 3\pi$$

```
x = u cos(v)

y = u sin(v)

z = v

S = (x,y,z)

a = expform(abs(cross(d(S,u),d(S,v))))

defint(a,u,0,1,v,0,3pi)

\frac{3\pi}{2^{1/2}} + \frac{3}{2}\pi \log (2^{1/2} + 1)

float

10.8177
```

### **19** Surface integral

A surface integral is like adding up all the wind on a sail. In other words, we want to compute

$$\iint \mathbf{F} \cdot \mathbf{n} \, dA$$

where  $\mathbf{F} \cdot \mathbf{n}$  is the amount of wind normal to a tiny parallelogram dA. The integral sums over the entire area of the sail. Let S be the surface of the sail parameterized by x and y. (In this model, the z direction points downwind.) By the properties of the cross product we have the following for the unit normal  $\mathbf{n}$  and for dA.

$$\mathbf{n} = \frac{\frac{\partial S}{\partial x} \times \frac{\partial S}{\partial y}}{\left|\frac{\partial S}{\partial x} \times \frac{\partial S}{\partial y}\right|} \qquad dA = \left|\frac{\partial S}{\partial x} \times \frac{\partial S}{\partial y}\right| \, dx \, dy$$

Hence

$$\iint \mathbf{F} \cdot \mathbf{n} \, dA = \iint \mathbf{F} \cdot \left(\frac{\partial S}{\partial x} \times \frac{\partial S}{\partial y}\right) \, dx \, dy$$

The following exercise is from *Advanced Calculus* by Wilfred Kaplan, p. 313. Evaluate the surface integral

$$\iint_{S} \mathbf{F} \cdot \mathbf{n} \, d\sigma$$

where  $\mathbf{F} = xy^2 z \mathbf{i} - 2x^3 \mathbf{j} + yz^2 \mathbf{k}$ , S is the surface  $z = 1 - x^2 - y^2$ ,  $x^2 + y^2 \le 1$  and **n** is upper.

Note that the surface intersects the xy plane in a circle. By the right hand rule, crossing x into y yields **n** pointing upwards hence

$$\mathbf{n} \, d\sigma = \left(\frac{\partial S}{\partial x} \times \frac{\partial S}{\partial y}\right) \, dx \, dy$$

The following code computes the surface integral. The symbols f and h are used as temporary variables.

```
z = 1 - x^{2} - y^{2}
F = (x y^{2} z, -2 x^{3}, y z^{2})
S = (x,y,z)
f = dot(F, cross(d(S,x), d(S,y)))
h = sqrt(1 - x^{2})
defint(f, y, -h, h, x, -1, 1)
\frac{1}{48}\pi
```

# 20 Index

# abs(x)

Returns the absolute value or vector length of x.

X = (x,y,z)abs(X)

 $\left(x^2 + y^2 + z^2\right)^{1/2}$ 

# $\operatorname{adj}(m)$

Returns the adjunct of matrix m. Adjunct is equal to determinant times inverse.

```
A = ((a,b),(c,d))
adj(A) == det(A) inv(A)
```

1

# **and**(*a*, *b*, . . .)

Returns 1 if all arguments are true (nonzero). Returns 0 otherwise.

#### and(1=1,2=2)

1

# $\arccos(x)$

Returns the arc cosine of x.

 $\arccos(1/2)$ 

# $\frac{1}{3}\pi$

# $\operatorname{arccosh}(x)$

Returns the arc hyperbolic cosine of x.

### $\arcsin(x)$

Returns the arc sine of x.

 $\arcsin(1/2)$ 

 $\frac{1}{6}\pi$ 

### $\operatorname{arcsinh}(x)$

Returns the arc hyperbolic sine of x.

# $\arctan(y, x)$

Returns the arc tangent of y over x. If x is omitted then x = 1 is used.

arctan(1,0)

# $\frac{1}{2}\pi$

# $\operatorname{arctanh}(x)$

Returns the arc hyperbolic tangent of x.

### $\arg(z)$

Returns the angle of complex z.

#### arg(2 - 3i)

 $-\arctan(3,2)$ 

# binding(s)

The result of evaluating a symbol can differ from the symbol's binding. For example, the result may be expanded. The **binding** function returns the actual binding of a symbol.

```
p = quote((x + 1)^{2})
p
p = x^{2} + 2x + 1
binding(p)
```

 $(x+1)^2$ 

### break

Break out of a loop or for function.

k = 0 loop(k = k + 1, test(k == 4, break), print(k)) k = 1 k = 2 k = 3

### $\operatorname{ceiling}(x)$

Returns the smallest integer greater than or equal to x.

```
ceiling(1/2)
```

1

```
\operatorname{check}(x)
```

If x is true (nonzero) then continue, else stop. Expression x can include the relational operators =, ==, <, <=, >, >=. Use the not function to test for inequality.

A = exp(i pi)
B = -1
check(A == B) -- stop here if A not equal to B

# choose(n,k)

Returns the binomial coefficient n choose k.

```
choose(52,5) -- number of poker hands
```

2598960

#### clear

Clears all symbol definitions.

# $\operatorname{clock}(z)$

Returns complex z in polar form with base of negative 1 instead of e.

clock(2 - 3i)

 $13^{1/2} (-1)^{-\arctan(3,2)/\pi}$ 

# cofactor(m, i, j)

Returns the cofactor of matrix m for row i and column j.

```
A = ((a,b),(c,d))
cofactor(A,1,2) == adj(A)[2,1]
```

1

# $\operatorname{conj}(z)$

Returns the complex conjugate of z.

```
conj(2 - 3i)
```

2 + 3i

# contract(a, i, j)

Returns tensor a summed over indices i and j. If i and j are omitted then 1 and 2 are used. The expression contract(m) computes the trace of matrix m.

```
A = ((a,b),(c,d))
contract(A)
```

a+d

```
\cos(x)
```

Returns the cosine of x.

cos(pi/4)

 $\frac{1}{2^{1/2}}$ 

# $\cosh(x)$

Returns the hyperbolic cosine of x.

```
expform(cosh(x))
```

 $\frac{1}{2}\exp(-x) + \frac{1}{2}\exp(x)$ 

### cross(u, v)

Returns the cross product of vectors u and v.

# $\operatorname{curl}(v)$

Returns the curl of vector v with respect to symbols  $\mathbf{x}$ ,  $\mathbf{y}$ , and  $\mathbf{z}$ .

 $\mathbf{d}(f, x, \ldots)$ 

Returns the partial derivative of f with respect to x and any additional arguments.

#### d(sin(x), x)

 $\cos(x)$ 

Multiderivatives are computed by extending the argument list.

#### d(sin(x),x,x)

 $-\sin(x)$ 

A numeric argument n computes the nth derivative with respect to the previous symbol.

d(sin(x y),x,2,y,2)

 $x^2y^2\sin(xy) - 4xy\cos(xy) - 2\sin(xy)$ 

Argument f can be a tensor of any rank. Argument x can be a vector. When x is a vector the result is the gradient of f.

F = (f(),g(),h()) X = (x,y,z) d(F,X) $\begin{bmatrix} d(f(),x) & d(f(),y) & d(f(),z) \\ d(g(),x) & d(g(),y) & d(g(),z) \\ d(h(),x) & d(h(),y) & d(h(),z) \end{bmatrix}$ 

Symbol d can be used as a variable name. Doing so does not conflict with function d.

Symbol d can be redefined as a different function. The function derivative, a synonym for d, can be used to obtain a partial derivative.

# $\operatorname{defint}(f, x, a, b, \ldots)$

Returns the definite integral of f with respect to x evaluated from a to b. The argument list can be extended for multiple integrals. The following example integrates over theta then over phi.

```
defint(sin(theta), theta, 0, pi, phi, 0, 2 pi)
```

 $4\pi$ 

# denominator(x)

Returns the denominator of expression x.

```
denominator(a/b)
```

b

# $\det(m)$

Returns the determinant of matrix m.

```
A = ((a,b),(c,d))
det(A)
```

ad - bc

# dim(a, n)

Returns the dimension of the nth index of tensor a. Index numbering starts with 1.

```
A = ((1,2), (3,4), (5,6))
dim(A,1)
```

3

# $\operatorname{div}(v)$

Returns the divergence of vector v with respect to symbols  $\mathbf{x}$ ,  $\mathbf{y}$ , and  $\mathbf{z}$ .

# **do**(*a*, *b*, . . .)

Evaluates each argument from left to right. Returns the result of the final argument.

```
do(A=1,B=2,A+B)
```

3

# $dot(a, b, \ldots)$

Returns the dot product of vectors, matrices, and tensors. Also known as the matrix product. Arguments are evaluated from right to left. The following example solves for X in AX = B.

```
A = ((1,2),(3,4))
B = (5,6)
X = dot(inv(A),B)
X
\begin{bmatrix} -4\\ \frac{9}{2} \end{bmatrix}
```

#### eigenvec(m)

Returns eigenvectors for matrix m. Matrix m is required to be numerical, real, and symmetric. The return value is a matrix with each column an eigenvector. Eigenvalues are obtained as shown.

```
A = ((1,2,3), (2,6,4), (3,4,5))

Q = \text{eigenvec}(A)

D = \text{dot}(\text{transpose}(Q), A, Q) -- \text{eigenvalues on the diagonal of } D

\text{dot}(Q, D, \text{transpose}(Q))
```

 $\begin{bmatrix} 1 & 2 & 3 \\ 2 & 6 & 4 \\ 3 & 4 & 5 \end{bmatrix}$ 

# $\operatorname{erf}(x)$

Error function of x. Returns a numerical value if x is a real number.

erf(1.0)

0.842701

d(erf(x), x)

$$\frac{2\exp(-x^2)}{\pi^{1/2}}$$

### $\operatorname{erfc}(x)$

Complementary error function of x. Returns a numerical value if x is a real number.

erfc(1.0)

0.157299

d(erfc(x),x)

$$-\frac{2\exp(-x^2)}{\pi^{1/2}}$$

 $eval(f, x, a, y, b, \ldots)$ 

Returns f evaluated with x replaced by a, y replaced by b, etc. All arguments can be expressions.

 $f = sqrt(x^2 + y^2)$ eval(f,x,3,y,4)

5

In the following example, eval is used to replace x with cos(theta).

#### P(2,-1)

 $-\frac{1}{2}\cos(\theta)\sin(\theta)$ 

### $\exp(x)$

Returns the exponential of x.

#### exp(i pi)

-1

#### $\exp\cos(z)$

Returns the cosine of z in exponential form.

#### expcos(z)

 $\frac{1}{2}\exp(iz) + \frac{1}{2}\exp(-iz)$ 

### $\operatorname{expcosh}(z)$

Returns the hyperbolic cosine of z in exponential form.

#### expcosh(z)

 $\frac{1}{2}\exp(-z) + \frac{1}{2}\exp(z)$ 

# expform(x)

Returns expression x with trigonometric and hyperbolic functions converted to exponentials.

```
expform(cos(x) + i sin(x))
```

 $\exp(ix)$ 

# $\exp(z)$

Returns the sine of z in exponential form.

expsin(z)

```
-\tfrac{1}{2}i\exp(iz)+\tfrac{1}{2}i\exp(-iz)
```

# $\operatorname{expsinh}(z)$

Returns the hyperbolic sine of z in exponential form.

#### expsinh(z)

$$-\frac{1}{2}\exp(-z) + \frac{1}{2}\exp(z)$$

# exptan(z)

Returns the tangent of z in exponential form.

#### exptan(z)

 $\frac{i}{\exp(2iz)+1} - \frac{i\exp(2iz)}{\exp(2iz)+1}$ 

# $\operatorname{exptanh}(z)$

Returns the hyperbolic tangent of z in exponential form.

#### exptanh(z)

$$-\frac{1}{\exp(2z)+1} + \frac{\exp(2z)}{\exp(2z)+1}$$

# factorial(n)

Returns the factorial of n. The expression n! can also be used.

#### 20!

#### 2432902008176640000

# float(x)

Returns expression x with rational numbers and integers converted to floating point values. The symbol **pi** and the natural number are also converted.

float(212^17)  $3.52947 \times 10^{39}$ 

# floor(x)

Returns the largest integer less than or equal to x.

floor(1/2)

0

```
for(a, b, c, d, e, f, ...)
```

For a equals b through c inclusive, evaluate the remaining arguments in a loop. Arguments b and c are integers. Symbol a is advanced by plus or minus 1 in the direction of c each time through the loop. Use **break** to break out of the loop early. The original value of a is restored after **for** completes. Note that if symbol **i** is used for a then the imaginary unit is overridden in the scope of **for**.

```
for(k,1,3,print(k))
```

k = 1k = 2k = 3

# $\operatorname{grad}(f)$

Returns the gradient d(f,(x,y,z)).

grad(f())

 $\begin{bmatrix} \mathbf{d}(f(),x) \\ \mathbf{d}(f(),y) \\ \mathbf{d}(f(),z) \end{bmatrix}$ 

# $hadamard(a, b, \ldots)$

Returns the Hadamard (element-wise) product.

```
X = (a,b,c)
hadamard(X,X)
```

```
\begin{bmatrix} a^2 \\ b^2 \\ c^2 \end{bmatrix}
```

# i

Symbol i is initialized to the imaginary unit  $\sqrt{-1}$ .

#### exp(i pi)

-1

Note: It is ok to clear or redefine i and use the symbol for something else.

### $\operatorname{imag}(z)$

Returns the imaginary part of complex z.

imag(2 - 3i)

-3

### infixform(x)

Converts expression x to a string and returns the result.

```
p = (x + 1)^2
infixform(p)
```

 $x^2 + 2 x + 1$ 

### **inner** $(a, b, \ldots)$

Returns the inner product of vectors, matrices, and tensors. Also known as the matrix product.

```
A = ((a,b),(c,d))B = (x,y)inner(A,B)
```

 $\begin{bmatrix} ax + by \\ cx + dy \end{bmatrix}$ 

Note: inner and dot are the same function.

# integral(f, x)

Returns the integral of f with respect to x.

```
integral(x^2,x)
```

 $\frac{1}{3}x^3$ 

# inv(m)

Returns the inverse of matrix m.

A = ((1,2),(3,4)) inv(A)  $\begin{bmatrix} -2 & 1 \\ \frac{3}{2} & -\frac{1}{2} \end{bmatrix}$ 

# j

Set j=sqrt(-1) to use j for the imaginary unit instead of i.

```
j = sqrt(-1)
1/sqrt(-1)
```

-j

# **kronecker** $(a, b, \ldots)$

Returns the Kronecker product of vectors and matrices.

```
A = ((1,2), (3,4)) 
B = ((a,b), (c,d)) 
kronecker(A,B) 
\begin{bmatrix} a & b & 2a & 2b \\ c & d & 2c & 2d \\ 3a & 3b & 4a & 4b \end{bmatrix}
```

3c 3d 3c 4d

#### last

The result of the previous calculation is stored in last.

#### 212^17

3529471145760275132301897342055866171392

```
last^(1/17)
```

212

Symbol last is an implied argument when a function has no argument list.

#### 212^17

3529471145760275132301897342055866171392

### float

 $3.52947 \times 10^{39}$ 

# $\log(x)$

Returns the natural logarithm of x.

log(x^y)

 $y\log(x)$ 

# **loop** $(a, b, c, \ldots)$

Evaluate arguments in a loop. Use break to break out of the loop.

```
k = 0
loop(k = k + 1, test(k == 4, break), print(k))
k = 1
k = 2
k = 3
```

### mag(z)

Returns the magnitude of complex z. Function mag treats undefined symbols as real while abs does not.

mag(x + i y)

 $(x^2 + y^2)^{1/2}$ 

# minor(m, i, j)

Returns the minor of matrix m for row i and column j.

```
A = ((1,2,3),(4,5,6),(7,8,9))
minor(A,1,1) == det(minormatrix(A,1,1))
```

1

### **minormatrix**(m, i, j)

Returns a copy of matrix m with row i and column j removed.

```
A = ((1,2,3), (4,5,6), (7,8,9))
minormatrix(A,1,1)
\begin{bmatrix} 5 & 6 \\ 8 & 9 \end{bmatrix}
```

### noexpand(x)

Evaluates expression x without expanding products of sums.

 $noexpand((x + 1)^2 / (x + 1))$ 

x + 1

# not(x)

Returns 0 if x is true (nonzero). Returns 1 otherwise.

not(1=1)

0

#### nroots(p, x)

Returns the approximate roots of polynomials with real or complex coefficients. Multiple roots are returned as a vector.

```
p = x^{5} - 1
nroots(p,x)
\begin{bmatrix} 1\\ -0.809017 + 0.587785 i\\ -0.809017 - 0.587785 i\\ 0.309017 + 0.951057 i\\ 0.309017 - 0.951057 i \end{bmatrix}
```

# number(x)

Returns 1 if x is a real number. Returns 0 otherwise.

```
number(1/2)
```

1

number(x)

0

### numerator(x)

Returns the numerator of expression x.

```
numerator(a/b)
```

a

**or**(*a*, *b*, . . .)

Returns 1 if at least one argument is true (nonzero). Returns 0 otherwise.

#### or(1=1,2=2)

1

# **outer**(*a*, *b*, . . .)

Returns the outer product of vectors, matrices, and tensors.

```
A = (a,b,c)B = (x,y,z)outer(A,B)
```

 $\begin{bmatrix} ax & ay & az \\ bx & by & bz \\ cx & cy & cz \end{bmatrix}$ 

# $\mathbf{pi}$

Symbol for  $\pi$ .

exp(i pi)

-1

# $\operatorname{polar}(z)$

Returns complex z in polar form.

polar(x - i y)  $(x^2 + y^2)^{1/2} \exp(-i \arctan(y, x))$ 

#### power

Use  $\widehat{}$  to raise something to a power. Use parentheses for negative powers.

x^(-2)

 $\frac{1}{x^2}$ 

### $\mathbf{print}(a, b, \ldots)$

Evaluate arguments and print the results. Useful for printing from inside a for loop.

```
for(j,1,3,print(j))
```

j = 1<br/>j = 2<br/>j = 3

# product(i, j, k, f)

For i equals j through k evaluate f. Returns the product of all f.

```
product(j,1,3,x + j)
```

 $x^3 + 6x^2 + 11x + 6$ 

The original value of i is restored after product completes. If symbol i is used for index variable i then the imaginary unit is overridden in the scope of product.

# product(y)

Returns the product of components of y.

```
y = (1,2,3,4)
product(y)
```

24

# quote(x)

Returns expression x without evaluating it first.

```
quote((x + 1)^2)
```

 $(x+1)^2$ 

### rank(a)

Returns the number of indices that tensor a has.

```
A = ((a,b),(c,d))
rank(A)
```

2

# rationalize(x)

Returns expression x with everything over a common denominator.

rationalize(1/a + 1/b + 1/2)  $\frac{2a + ab + 2b}{2ab}$ 

Note: rationalize returns an unexpanded expression. If the result is assigned to a symbol, evaluating the symbol will expand the result. Use binding to retrieve the unexpanded expression.

```
f = rationalize(1/a + 1/b + 1/2)
binding(f)
```

 $\frac{2a+ab+2b}{2ab}$ 

# $\operatorname{real}(z)$

Returns the real part of complex z.

```
real(2 - 3i)
```

2

# rect(z)

Returns complex z in rectangular form.

```
rect(exp(i x))
```

 $\cos(x) + i\sin(x)$ 

# roots(p, x)

Returns the rational roots of a polynomial. Multiple roots are returned as a vector.

```
p = (x + 1) (x - 2)
roots(p,x)
\begin{bmatrix} -1 \\ 2 \end{bmatrix}
```

If no roots are found then nil is returned. A nil result is not printed so the following example uses infixform to print nil as a string.

```
p = x<sup>2</sup> + 1
infixform(roots(p,x))
```

 $\operatorname{nil}$ 

# $rotate(u, s, k, \ldots)$

Rotates vector u and returns the result. Vector u is required to have  $2^n$  elements where n is an integer from 1 to 15. Arguments  $s, k, \ldots$  are a sequence of rotation codes where s is an upper case letter and k is a qubit number from 0 to n - 1. Rotations are evaluated from left to right. See the section on quantum computing for a list of rotation codes.

```
psi = (1,0,0,0)
rotate(psi,H,0)
```

```
\begin{bmatrix} \frac{1}{2^{1/2}} \\ \frac{1}{2^{1/2}} \\ 0 \\ 0 \end{bmatrix}
```

### run(x)

Run script x where x evaluates to a filename string. Useful for importing function libraries.

```
run("/Users/heisenberg/EVA2.txt")
```

For Eigenmath installed from the Mac App Store, run files need to be put in the directory ~/Library/Containers/eigenmath/Data/ and the filename does not require a path.

run("EVA2.txt")

sgn(x)

Returns the sign of x if x is a real number.

sgn(0)

0

sgn(1/2)

1

sgn(-1/2)

-1

sgn(-x)

 $\operatorname{sgn}(-x)$ 

# simplify(x)

Returns expression x in a simpler form.

```
simplify(sin(x)^2 + cos(x)^2)
```

#### 1

# $\sin(x)$

Returns the sine of x.

sin(pi/4)

 $\frac{1}{2^{1/2}}$ 

# $\sinh(x)$

Returns the hyperbolic sine of x.

#### expform(sinh(x))

 $-\tfrac{1}{2}\exp(-x) + \tfrac{1}{2}\exp(x)$ 

# sqrt(x)

Returns the square root of x.

#### sqrt(10!)

 $720 \ 7^{1/2}$ 

### stop

In a script, it does what it says.

### $\mathbf{sum}(i, j, k, f)$

For i equals j through k evaluate f. Returns the sum of all f.

#### sum(j,1,5,x^j)

 $x^5 + x^4 + x^3 + x^2 + x$ 

The original value of i is restored after sum completes. If symbol i is used for index variable i then the imaginary unit is overridden in the scope of sum.

# $\operatorname{sum}(y)$

Returns the sum of components of y.

```
y = (1,2,3,4)
sum(y)
```

10

# $\tan(x)$

Returns the tangent of x.

simplify(tan(x) - sin(x)/cos(x))

0

### tanh(x)

Returns the hyperbolic tangent of x.

expform(tanh(x))

$$-\frac{1}{\exp(2x)+1} + \frac{\exp(2x)}{\exp(2x)+1}$$

$$test(a, b, c, d, \ldots)$$

If argument *a* is true (nonzero) then *b* is returned, else if *c* is true then *d* is returned, etc. If the number of arguments is odd then the final argument is returned if all else fails. Expressions can include the relational operators =, ==, <, <=, >, >=. Use the not function to test for inequality. (The equality operator == is available for contexts in which = is the assignment operator.)

```
A = 1
B = 1
test(A=B,"yes","no")
```

yes

# tgamma(x)

Returns the Gamma function of x if x is a real number.

tgamma(4)

6

#### trace

Set trace=1 in a script to print the script as it is evaluated. Useful for debugging.

#### trace = 1

Note: The contract function is used to obtain the trace of a matrix.

### **transpose**(a, i, j)

Returns the transpose of tensor a with respect to indices i and j. If i and j are omitted then 1 and 2 are used. Hence a matrix can be transposed with a single argument.

```
A = ((a,b),(c,d))
transpose(A)
```

 $\begin{bmatrix} a & c \\ b & d \end{bmatrix}$ 

Note: The argument list can be extended for multiple transpose operations. Arguments are evaluated from left to right. For example, transpose(A,1,2,2,3) is equivalent to transpose(transpose(A,1,2),2,3)

#### tty

Set tty=1 to show results in string format. Set tty=0 to turn off. Can be useful when displayed results exceed window size.

```
tty = 1
(x + 1)^2
```

x^2 + 2 x + 1

### unit(n)

Returns an n by n identity matrix.

#### unit(3)

 $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ 

# $\mathbf{zero}(a, b, \ldots)$

Returns a null tensor with dimensions a, b, etc.

# zero(2,3,3)

ze	ro	(2,	3,3)
ſ	$\begin{bmatrix} 0\\ 0\\ 0 \end{bmatrix}$	0 0 0	$\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$
	$\begin{bmatrix} 0\\ 0\\ 0 \end{bmatrix}$	0 0 0	$\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$

# 21 Tricks

- 1. Use == to test for equality. In effect, A==B is equivalent to simplify(A-B)==0.
- 2. In a script, line breaking is allowed where the scanner needs something to complete an expression. For example, the scanner will automatically go to the next line after an operator.
- 3. Setting trace=1 in a script causes each line to be printed just before it is evaluated. Useful for debugging.
- 4. The last result is stored in symbol last.
- 5. Use contract(A) to get the mathematical trace of matrix A.
- 6. Use binding(s) to get the unevaluated binding of symbol s.
- 7. Use s=quote(s) to clear symbol s.
- 8. Use float(pi) to get the floating point value of  $\pi$ . Set pi=float(pi) to evaluate expressions with a numerical value for  $\pi$ . Set pi=quote(pi) to make  $\pi$  symbolic again.
- 9. Use e=exp(1) to assign the natural number e to symbol e.
- 10. Assign strings to unit names so they are printed normally. For example, setting meter="meter" causes symbol meter to be printed as meter instead of  $m_{eter}$ .
- 11. Use expsin and expcos instead of sin and cos. Trigonometric simplifications occur automatically when exponentials are used. See also expform for converting an expression to exponential form.
- 12. Use rect(expform(f)) to maybe find a new form of trigonometric expression f.

f = cos(theta/2)^2
rect(expform(f))

 $\frac{1}{2}\cos(\theta) + \frac{1}{2}$ 

13. Complex number functions conj, mag, etc. treat undefined symbols as representing real numbers. To define symbols that represent complex numbers, use separate symbols for the real and imaginary parts.

```
z = x + i y

conj(z) z

x^2 + y^2
```

```
z = A \exp(i \text{ theta})
conj(z) z
A^2
```

14. Use mag for component magnitude, abs for vector magnitude.

```
y = (a, -b)
mag(y)
\begin{bmatrix} a \\ b \end{bmatrix}
abs(y)
[a^2 + b^2]^{1/2}
```

15. Use draw(y[floor(x)],x) to plot the values of vector y.

y = (1,2,3,4)
draw(y[floor(x)],x)

16. The following example demonstrates some eval tricks. (See exercise 4-10 of *Quantum Mechanics* by Richard Fitzpatrick.)

Let

$$\psi = \frac{\phi_1 + \phi_2}{2} \exp\left(-\frac{iE_1t}{\hbar}\right) + \frac{\phi_1 - \phi_2}{2} \exp\left(-\frac{iE_2t}{\hbar}\right)$$

where  $\phi_1$  and  $\phi_2$  are orthogonal. Let operator A have the following eigenvalues.

$$A\phi_1 = a_1\phi_1$$
$$A\phi_2 = a_2\phi_2$$

Verify that

$$\langle A \rangle = \int \psi^* A \psi \, dx = \frac{a_1 + a_2}{2} + \frac{a_1 - a_2}{2} \cos\left(\frac{(E_1 - E_2)t}{\hbar}\right)$$

Because  $\phi_1$  and  $\phi_2$  are normalized we have  $\int \phi_1^* \phi_1 dx = 1$  and  $\int \phi_2^* \phi_2 dx = 1$ . By orthogonality we have  $\int \phi_1^* \phi_2 dx = 0$ . Hence the integral can be accomplished with eval.