The adjoint operator in the freealg package

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Abstract

In this very short document I discuss the adjoint operator `ad()` and illustrate some of its properties.

Keywords: Adjoint operator, free algebra.

```
> ad

function (x)
{
    function(y) {
        jj <- new("dot")
        return(jj[x, y])
    }
}
<bytecode: 0x563de62fe018>
<environment: namespace:freealg>
```

The adjoint operator: definition

An associative algebra $\mathcal{A}$ and $X, Y \in \mathcal{A}$, we define the *Lie Bracket* $[X, Y]$ as $XY - YX$. In the `freealg` package this is implemented with the `.[]` construction:

```
> X <- as.freealg("X")
> Y <- as.freealg("Y")
> .[X,Y]

free algebra element algebraically equal to
- 1*YX + 1*XY
```

The Jacobi identity

The Lie bracket is bilinear and satisfies the Jacobi condition:

```
> X <- rfalg(3)
> Y <- rfalg(3)
> Z <- rfalg(3)
> X # Y and Z are similar objects

free algebra element algebraically equal to
+ 1*c + 2*cab + 3*cccb

> .[X,Y] # quite complicated

free algebra element algebraically equal to
- 1*bbcac - 2*bbcacab - 3*bbcacccb + 2*cabbbca + 4*cabca + 6*cabcb - 2*cac -
4*cacab - 6*cacccb + 1*cbbca - 3*cbc - 6*cbcab - 9*cbcccb + 2*cca + 3*ccb +
3*cccbbbca + 6*cccbca + 9*cccbcb

> .[X,.[Y,Z]] + .[Y,.[Z,X]] + .[Z,.[X,Y]]  # Zero by Jacobi

free algebra element algebraically equal to
0
```

The adjoint: definition

Now we define the adjoint as follows. Given a Lie algebra $\mathfrak{g}$, and $X \in \mathcal{A}$, we define a linear map $\mathrm{ad}_X\colon \mathfrak{g} \longrightarrow \mathfrak{g}$ with

$$\mathrm{ad}_X(Y) = [X, Y]$$

In the `freealg` package, this is implemented using the `ad()` function:

```
> ad(X)

function (y)
{
    jj <- new("dot")
    return(jj[x, y])
}
<bytecode: 0x563de62fdb10>
<environment: 0x563de216d850>
```

See how function `ad()` returns a *function*. We can play with this:

```
> f <- ad(X)
> f(Y)
```

```
free algebra element algebraically equal to
- 1*bbcac - 2*bbcacab - 3*bbcacccb + 2*cabbbca + 4*cabca + 6*cabcb - 2*cac -
4*cacab - 6*cacccb + 1*cbbca - 3*cbc - 6*cbcab - 9*cbcccb + 2*cca + 3*ccb +
3*cccbbbca + 6*cccbca + 9*cccbcb
```

```
> f(Y) == X*Y-Y*X
```

```
[1] TRUE
```

The first thing to note is that ad_X is NOT a Lie homomorphism. If ϕ is a Lie homomorphism then $\phi([x,y]) = [\phi(x), \phi(y)]$. There is no reason to expect the adjoint to be a Lie homomorphism, but it does not hurt to check:

```
> phi <- ad(Z)
> phi(.[X,Y]) == .[phi(X),phi(Y)]
```

```
[1] FALSE
```

With this definition, it is easy to calculate, say, $[Z,[Z,[Z,[Z,[Z,X]]]]]$:

```
> f <- ad(as.freealg("x"))
> f(f(f(f(f(as.freealg("y"))))))
```

```
free algebra element algebraically equal to
+ 1*xxxxxy - 5*xxxxyx + 10*xxxyxx - 10*xxyxxx + 5*xyxxxx - 1*yxxxxx
```

The adjoint operator is a derivation

A *derivation* of a Lie bracket is a function $\phi\colon \mathfrak{g} \longrightarrow \mathfrak{g}$ that satisfies

$$\phi([Y,Z]) = [\phi(Y), Z] + [Y, \phi(Z)].$$

We will verify that ad_X is indeed a derivation:

```
> phi <- ad(X)
> phi(.[Y,Z]) == .[phi(Y),Z] + .[Y,phi(Z)]
```

```
[1] TRUE
```

The adjoint operator $\mathrm{ad}\colon \mathfrak{g} \longrightarrow \mathrm{End}(\mathfrak{g})$ is a Lie homomorphism

We are asserting that

$$\mathrm{ad}_{[X,Y]} = [\mathrm{ad}_X, \mathrm{ad}_Y]$$

In package idiom we would have:

```
> ad(.[X,Y])(Z) == .[ad(X),ad(Y)](Z)

[1] TRUE
```

Observe that "`.[ad(X),ad(Y)]`" is a function:

```
> .[ad(X),ad(Y)]

function (z)
{
    i(j(z)) - j(i(z))
}
<environment: 0x563de661dc20>
```

which we evaluate (on the right hand side) at `Z`.

Adjoints in other contexts

Function `ad()` works in a more general context than the free algebra. For example, we might use it for matrices:

```
> f <- ad(matrix(c(4,6,2,3),2,2))
> M <- matrix(1:4,2,2)
> f(M)

     [,1] [,2]
[1,]  -14    9
[2,]  -20   14
```

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