Relational algebra by way of adjunctions

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Relational Algebra by Way of Adjunctions

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1. Summary

- bulk types (sets, bags, lists) are monads
- monads have nice mathematical foundations via adjunctions
- monads support comprehensions
- comprehension syntax provides a query notation

```
[ (customer.name, invoice.amount)
 | customer ← customers,
    invoice ← invoices,
    customer.cid = invoice.customer,
    invoice.due <= today ]
```

- monad structure explains selection, projection
- less obvious how to explain join
2. Galois connections

Relating monotonic functions between two ordered sets:

\[(A, \leq) \perp (B, \sqsubseteq)\]

means \(f \ b \leq a \iff b \sqsubseteq g \ a\)

For example,

\[(\mathbb{R}, \leq) \perp (\mathbb{Z}, \leq)\]

\[(\mathbb{Z}, \leq) \perp (\mathbb{Z}, \leq)\]

“Change of coordinates” can sometimes simplify reasoning; eg rhs gives \(n \times k \leq m \iff n \leq m \div k\), and multiplication is easier to reason about than rounding division.
3. Category theory from ordered sets

A *category* $\mathbf{C}$ consists of

- a set* $|\mathbf{C}|$ of *objects*,
- a set* $\mathbf{C}(X, Y)$ of *arrows* $X \to Y$ for each $X, Y : |\mathbf{C}|$,
- identity arrows $id_X : X \to X$ for each $X$
- composition $f \cdot g : X \to Z$ of compatible arrows $g : X \to Y$ and $f : Y \to Z$,
- such that composition is associative, with identities as units.

Think of a directed graph, with vertices as objects and paths as arrows.

An ordered set $(A, \leq)$ is a degenerate category, with objects $A$ and a unique arrow $a \to b$ iff $a \leq b$.

\[ \ldots \rightarrow -2 \rightarrow -1 \rightarrow 0 \rightarrow 1 \rightarrow 2 \rightarrow \ldots \]

Many categorical concepts are generalisations from ordered sets.

*proviso...
4. Concrete categories

Ordered sets are a *concrete category*: roughly,

- the objects are *sets with additional structure*
- the arrows are *structure-preserving mappings*

Many useful categories are of this form.

For example, the category \( \mathbf{CMon} \) has commutative monoids \((M, \otimes, \epsilon)\) as objects, and homomorphisms \( h : (M, \otimes, \epsilon) \to (M', \oplus, \epsilon') \) as arrows:

\[
\begin{align*}
h (m \otimes n) &= h m \oplus h n \\
h \epsilon &= \epsilon'
\end{align*}
\]

Trivially, category \( \mathbf{Set} \) has sets as objects, and total functions as arrows.
5. Functors

Categories are themselves structured objects...

A functor $F : C \rightarrow D$ is an operation on both objects and arrows, preserving the structure: $F f : F X \rightarrow F Y$ when $f : X \rightarrow Y$, and

\[
F \ id_X = id_{F X}\\
F (f \cdot g) = F f \cdot F g
\]

For example, forgetful functor $U : \text{CMon} \rightarrow \text{Set}$:

\[
U (M, \otimes, \epsilon) = M\\
U (h : (M, \otimes, \epsilon) \rightarrow (M', \oplus, \epsilon')) = h : M \rightarrow M'
\]

Conversely, $\text{Free} : \text{Set} \rightarrow \text{CMon}$ generates the free commutative monoid (ie bags) on a set of elements:

Free $A = (\text{Bag} A, \cup, \emptyset)$
Free $(f : A \rightarrow B) = map f : \text{Bag} A \rightarrow \text{Bag} B$
6. Adjunctions

Adjunctions are the categorical generalisation of Galois connections. Given categories $C, D$, and functors $L : D \to C$ and $R : C \to D$, adjunction

$$C \bot D \quad \text{means}^* \quad [-] : C(LX, Y) \simeq D(X, RY) : [-]$$

A familiar example is given by currying:

$$
\begin{align*}
\text{Set} \quad \bot \quad \text{Set} \\
\text{with } curry : \text{Set}(X \times P, Y) \simeq \text{Set}(X, Y^P) : curry^\circ
\end{align*}
$$

hence definitions and properties of $apply = uncurry \ id_{Y^P} : Y^P \times P \to Y$
7. Products and coproducts

\[
\text{with}
\]

\[
fork : \text{Set}^2(\Delta A, (B, C)) \simeq \text{Set}(A, B \times C) : fork^\circ
\]
\[
junc^\circ : \text{Set}(A + B, C) \simeq \text{Set}^2((A, B), \Delta C) : junc
\]

hence

\[
dup = fork \ id_{A,A} : \text{Set}(A, A \times A)
\]
\[
(fst, snd) = fork^\circ \ id_{B \times C} : \text{Set}^2(\Delta(B, C), (B, C))
\]

give tupling and projection. Dually for sums and injections, and generally for any arity—even zero.
8. Free commutative monoids

Adjunctions often capture embedding/projection pairs:

\[
\text{CMon} \quad \downarrow \quad \text{Set}
\]

with \([-] : \text{CMon}(\text{Free } A, (M, \otimes, \epsilon)) \cong \text{Set}(A, U (M, \otimes, \epsilon)) : [-]\)

Unit and counit:

\[
\text{single } A = [i_{\text{Free } A}] : A \to U (\text{Free } A)
\]

\[
\text{reduce } M = [i_{M}] : \text{Free } (U M) \to M \quad \text{-- for } M = (M, \otimes, \epsilon)
\]

whence, for \(h : \text{Free } A \to M\) and \(f : A \to U M = M\),

\[
h = \text{reduce } M \cdot \text{Free } f \iff U h \cdot \text{single } A = f
\]

ie 1-to-1 correspondence between homomorphisms from the free commutative monoid (bags) and their behaviour on singletons.
9. Aggregation

Aggregations are bag homomorphisms:

<table>
<thead>
<tr>
<th>aggregation</th>
<th>monoid</th>
<th>action on singletons</th>
</tr>
</thead>
<tbody>
<tr>
<td>count</td>
<td>((\mathbb{N}, 0, +))</td>
<td>({ a } \rightarrow 1)</td>
</tr>
<tr>
<td>sum</td>
<td>((\mathbb{R}, 0, +))</td>
<td>({ a } \rightarrow a)</td>
</tr>
<tr>
<td>max</td>
<td>((\mathbb{Z}, \text{minBound, max}))</td>
<td>({ a } \rightarrow a)</td>
</tr>
<tr>
<td>min</td>
<td>((\mathbb{Z}, \text{maxBound, min}))</td>
<td>({ a } \rightarrow a)</td>
</tr>
<tr>
<td>all</td>
<td>((\mathbb{B}, \text{True, } \land))</td>
<td>({ a } \rightarrow a)</td>
</tr>
<tr>
<td>any</td>
<td>((\mathbb{B}, \text{False, } \lor))</td>
<td>({ a } \rightarrow a)</td>
</tr>
</tbody>
</table>

Selection is a homomorphism, to bags, using action

\[
guard : (A \rightarrow \mathbb{B}) \rightarrow \text{Bag } A \rightarrow \text{Bag } A
\]

\[
guard p a = \text{if } p a \text{ then } \{ a \} \text{ else } \emptyset
\]

Laws about selections follow from laws of homomorphisms (and of coproducts, since \(\mathbb{B} = 1 + 1\)).
10. Monads

Bags form a monad \((Bag, union, single)\) with

\[
\begin{align*}
Bag &= U \cdot \text{Free} \\
union & : \text{Bag} \ (\text{Bag} \ A) \to \text{Bag} \ A \\
single & : A \to \text{Bag} \ A
\end{align*}
\]

which justifies the use of comprehension notation \(\{ f \ a \ b \mid a \leftarrow x, b \leftarrow g \ a \}^+\).

In fact, for any adjunction \(L \dashv R\) between \(C\) and \(D\), we get a monad \((T, \mu, \eta)\) on \(D\), where

\[
\begin{align*}
T &= R \cdot L \\
\mu A &= R \ [id_A] \ L : T \ (T \ A) \to T \ A \\
\eta A &= [id_A] : A \to T \ A
\end{align*}
\]
11. Maps

Database indexes are essentially maps $\text{Map } K V = V^K$. Maps $(-)^K$ from $K$ form a monad (the $\text{Reader}$ monad in Haskell), so arise from an adjunction.

The *laws of exponents* arise from this adjunction, and from those for products and coproducts:

\[
\begin{align*}
\text{Map } 0 V & \simeq 1 \\
\text{Map } 1 V & \simeq V \\
\text{Map } (K_1 + K_2) V & \simeq \text{Map } K_1 V \times \text{Map } K_2 V \\
\text{Map } (K_1 \times K_2) V & \simeq \text{Map } K_1 (\text{Map } K_2 V) \\
\text{Map } K 1 & \simeq 1 \\
\text{Map } K (V_1 \times V_2) & \simeq \text{Map } K V_1 \times \text{Map } K V_2 : \text{merge}
\end{align*}
\]
12. Indexing

Relations are in 1-to-1 correspondence with set-valued functions:

\[
\begin{array}{c}
\text{Rel} \\ \downarrow J \\
\downarrow E \\
\text{Set}
\end{array}
\]

where \( J \) embeds, and \( E R : A \to \text{Set} B \) for \( R : A \sim B \).

Moreover, the correspondence remains valid for bags:

\[
\text{index} : \text{Bag} (K \times V) \simeq \text{Map} K (\text{Bag} V)
\]

Together, \( \text{index} \) and \( \text{merge} \) give efficient relational joins:

\[
x f \bowtie g y = \text{flatten} (\text{Map} K \text{ cp} (\text{merge} (\text{groupBy} f x, \text{groupBy} g y)))
\]

\[
\text{groupBy} : (V \to K) \to \text{Bag} V \to \text{Map} K (\text{Bag} V)
\]

\[
\text{flatten} : \text{Map} K (\text{Bag} V) \to \text{Bag} V
\]
13. Pointed sets and finite maps

Model *finite maps* $\text{Map}_*$ not as partial functions, but *total* functions to a *pointed* codomain $(A, a)$, i.e. a set $A$ with a distinguished element $a : A$.

Pointed sets and point-preserving functions form a category $\text{Set}_*$. There is an adjunction to $\text{Set}$, via

\[
\begin{array}{ccc}
\text{Set}_* & \perp & \text{Set} \\
& \mathsf{Maybe} & \\
& \downarrow & \\
\mathsf{U} & & \\
\end{array}
\]

where $\mathsf{Maybe} A \simeq 1 + A$ adds a point, and $\mathsf{U} (A, a) = A$ discards it.

In particular, $(\text{Bag} A, \emptyset)$ is a pointed set. Moreover, $\text{Bag} f$ is point-preserving, so we get a functor $\text{Bag}_* : \text{Set} \to \text{Set}_*$.

Indexing remains an isomorphism:

\[
\text{index} : \text{Bag}_* (K \times V) \simeq \text{Map}_* K (\text{Bag}_* V)
\]
14. Graded monads

A catch: finite maps aren’t a monad, because

\[ \eta a = \lambda k \to a : A \to \text{Map} \ K \ A \]

in general yields an infinite map.

However, finite maps are a graded monad*: for monoid \((M, \otimes, \epsilon)\),

\[ \mu X : T_m (T_n X) \to T_{m \otimes n} X \]
\[ \eta X : X \to T_\epsilon X \]

satisfying the usual laws. These too arise from adjunctions*.

We use the monoid \((\mathbb{K}, \times, 1)\) of finite key types under product.
15. Conclusions

- *monad comprehensions* for database queries
- structure arising from *adjunctions*
- equivalences from *universal properties*
- fitting in *relational joins*, via indexing
- to do: calculating *query optimisations*

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