Relational algebra by way of adjunctions
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Relational Algebra by Way of Adjunctions

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(joint work with Fritz Henglein, Ralf Hinze, Nicolas Wu)
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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*

\[
\begin{array}{l}
[ (customer.name, invoice.amount) \\
| customer \leftarrow customers, \\
\quad invoice \leftarrow invoices, \\
\quad customer.cid = invoice.customer, \\
\quad invoice.due \leq today ]
\end{array}
\]

- 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,

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

“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 $C$ consists of

- a set $|C|$ of objects,
- a set $C(X, Y)$ of arrows $X \to Y$ for each $X, Y : |C|$, 
- 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 $a \rightarrow b$ iff $a \leq b$.

$$\cdots \rightarrow -2 \rightarrow -1 \rightarrow 0 \rightarrow 1 \rightarrow 2 \rightarrow \cdots$$

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 \( \textbf{CMon} \) has commutative monoids \((M, \otimes, \epsilon)\) as objects, and homomorphisms \( h : (M, \otimes, \epsilon) \rightarrow (M', \oplus, \epsilon') \) as arrows:

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

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

Categories are themselves structured objects...

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

$$F \text{id}_X = \text{id}_{F X}$$
$$F (f \cdot g) = F f \cdot F g$$

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

$$U (M, \otimes, \epsilon) = M$$
$$U (h : (M, \otimes, \epsilon) \to (M', \oplus, \epsilon')) = h : M \to M'$$

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

$$\text{Free} A = (\text{Bag} A, \cup, \emptyset)$$
$$\text{Free} (f : A \to B) = \text{map} f : \text{Bag} A \to \text{Bag} B$$
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

$$\begin{array}{ccc}
C & \perp & D \\
\downarrow L & & \downarrow R \\
\downarrow R & & \downarrow L \\
\end{array}$$

means* $[-] : C(L X, Y) \cong D(X, R Y) : [-]$.

A familiar example is given by currying:

$$\begin{array}{ccc}
\text{Set} & \perp & \text{Set} \\
\downarrow - \times P & & \downarrow (\cdot)^P \\
\downarrow (\cdot)^P & & \downarrow - \times P \\
\end{array}$$

with $\text{curry} : \text{Set}(X \times P, Y) \cong \text{Set}(X, Y^P) : \text{curry}^\circ$.

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

\[
\begin{array}{ccc}
\text{Set} & \bot & \text{Set}^2 \\
\Delta & \rightarrow & \Delta \\
\times & \rightarrow & \bot \\
\end{array}
\]

with

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

hence

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

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:

$$\text{CMon} \perp \text{Set}$$

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

Unit and counit:

\[
\begin{align*}
single A &= [id_{\text{Free} A}] : A \to U (\text{Free} A) \\
reduce M &= [id_M] : \text{Free} (U M) \to M \quad \text{-- for } M = (M, \otimes, \epsilon)
\end{align*}
\]

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

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

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>${a} \mapsto 1$</td>
</tr>
<tr>
<td>sum</td>
<td>$(\mathbb{R}, 0, +)$</td>
<td>${a} \mapsto a$</td>
</tr>
<tr>
<td>max</td>
<td>$(\mathbb{Z}, \text{minBound}, \text{max})$</td>
<td>${a} \mapsto a$</td>
</tr>
<tr>
<td>min</td>
<td>$(\mathbb{Z}, \text{maxBound}, \text{min})$</td>
<td>${a} \mapsto a$</td>
</tr>
<tr>
<td>all</td>
<td>$(\mathbb{B}, \text{True}, \land)$</td>
<td>${a} \mapsto a$</td>
</tr>
<tr>
<td>any</td>
<td>$(\mathbb{B}, \text{False}, \lor)$</td>
<td>${a} \mapsto a$</td>
</tr>
</tbody>
</table>

Selection is a homomorphism, to bags, using action

$$\text{guard} : (A \to \mathbb{B}) \to \text{Bag } A \to \text{Bag } A$$

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

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

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

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

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

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

\[ \text{Rel} \quad \perp \quad \text{Set} \]

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:

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

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

\( \text{flatten} : \text{Map} K (\text{Bag} V) \to \text{Bag} V \)
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

![Diagram](attachment:adjunction_diagram.png)

where $\text{Maybe } A \cong 1 + A$ adds a point, and $U (A, a) = A$ 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:

$$\text{index} : \text{Bag}_* (K \times V) \cong \text{Map}_* K (\text{Bag}_* V)$$
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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