

# Links: A Tierless Web Programming Language Providing Language Integrated Query (now with Added Time Travel)

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**informatics**

# Links: A Tierless Web Programming Language with LINQ

## Outline

- Links as a programming language, example Links web app
- Three case studies
- Temporal features of Links (time travel)

## Terminology

- LINQ: language integrated query
- SQL: relational database programming language
- DOM: Document Object Model, HTML in web browsers
- Provenance: how a piece of data has been created/modified
- Digital/data curation: management and preservation of data

## Logistics

- Please ask questions at any time (including after the talk)
- Pointers to resources at the end of the slides
- Slides at [https://github.com/links-lang/splv2023\\_example\\_code](https://github.com/links-lang/splv2023_example_code)

# Links: The Team

**Then:** Phil Wadler, Jeremy Yallop, Sam Lindley, Ezra Cooper

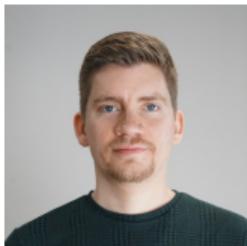


**Inbetween:** many PhD students, interns, visitors, postdocs and researchers who are now doing other things

**Now:** Sam Lindley, Phil Wadler and



James Cheney



Frank Emrich



Simon Fowler



Vashti Galpin



Daniel Hillerström



Wilmer Ricciotti

## Links: Timeline Part I

- 2006 Microsoft LINQ, C# and F#, reflection and quotation  
[Meier et al (SIGMOD 2006), Syme (2006)]
- 2006 **Development of Links based on Nested Relational Calculus and Kleisli**  
[Cooper et al (FMCO 2006), Buneman et al (TCS 1995), Wong (JFP 2000)]
- 2008 Formlets: abstraction for HTML forms [Cooper et al (APLAS 2008) ]
- 2009 **Use of effect typing for LINQ, normalisation of high-order NRC queries**  
[Cooper (DBPL 2009)]
- 2009 **RPC calculus, location-aware programming**  
[Cooper & Wadler (PPDP 2009), Choi et al (SCP 2020, PPDP 2021)]
- 2012 **Row-based effect types for database integration** [Lindley & Cheney (TLDI 2012)]
- 2013 **Theory of language-integrated query based on quotation**  
[Cheney et al (ICFP 2013, PEPM 2014)]
- 2014 **Query shredding: efficient nested multiset queries**  
[Cheney et al (SIGMOD 2014)]

## Links: Timeline Part II

- 2016 Effect handlers  
[Hillerström et al (TyDe 2016, FSCD 2017, APLAS 2018, JFP 2020, ICFP 2020)]
- 2016 Provenance [Fehrenbach & Cheney (PPDP 2016, SCP 2018, DBPL 2019)]
- 2017 **Session types, concurrency & distribution**  
[Lindley and Morris (2017), Fowler et al (POPL 2019)]
- 2018 Relational lenses, view update [Horn et al. (ICFP 2018, IFL 2019)]
- 2019 **Model-View-Update using session types** [Fowler (ECOOP 2020)]
- 2021 **Temporal database features: transaction-time, valid-time**  
[Cheney and Galpin (IPAW 2021), Fowler et al (GCPE 2022)]
- 2021 Semantics for null values, rewrite rules for normalising to SQL  
[Cheney & Ricciotti (DBPL 2021), Ricciotti & Cheney (JAR 2022)]
- 2021 Set and multiset semantics, deduplication and multiset difference  
[Ricciotti & Cheney (ESOP 2021, LMCS 2022)]
- 2023 Queries over finite maps, grouping and aggregation [Ricciotti (PPDP 2023)]

# Links: A Tierless Web Programming Language

# Links in a Nutshell

## The language

- Functional
- Expression-based
- Syntax loosely inspired by JavaScript
- Strongly typed, statically typed

## Type system

- Type inference
- Structural instead of nominal types
- Row polymorphism
- Effect typing, linearity, session types, first-class polymorphism, ...

## Structural typing in Links

```
# A record type containing fields id and descr
typename Task = (id: Int, descr: String);

fun makeTask(id : Int, descr: String) {
    (id=id, descr=descr)
}
```

Inferred return type of `makeTask`: `(id: Int, descr: String)`

- Equivalent to `Task`
- ... but definition of `Task` irrelevant for typing `makeTask`

Omitting type annotations yields more general type (slightly simplified):  
 $\forall a, b. (a, b) \rightarrow (id : a, descr : b)$

# A Glimpse at Row Polymorphism, Part I

```
typename Task = (id: Int, descr: String);

fun maxId(tasks) {
    switch (tasks) {
        case [] -> -1
        case task :: xs -> maximum(task.id, maxId(xs))
    }
}
```

What should the type of tasks be? Hint: Not [Task]!

All we learn: elements of tasks are records with **at least** field id : Int

Row variables  $\rho$  abstract over “unknown” parts of record.

Inferred type (slightly simplified):  $\forall \rho : \text{Row}.([(\text{id} : \text{Int} | \rho)]) \rightarrow \text{Int}$

## A Glimpse at Row Polymorphism, Part II

Inferred type of `maxId` (slightly simplified):  $\forall \rho : \text{Row}. ([(\text{id} : \text{Int} | \rho)]) \rightarrow \text{Int}$

As usual: Instantiate quantified variables to obtain different types for `maxId`

Variable  $\rho$  is instantiated with rows rather than ordinary types

→ Choosing  $\rho$  to be the empty row:

$$([(id : \text{Int})]) \rightarrow \text{Int}$$

→ Choosing  $\rho$  to be row (`descr : String`):

$$([(id : \text{Int}, descr : \text{String})]) \rightarrow \text{Int}$$

→ Choosing  $\rho$  to be row with fields other than `id`:

$$([(id : \text{Int}, first\_name : \text{String}, family\_name : \text{String})]) \rightarrow \text{Int}$$

## Effect Typing

Links' type system tracks what **side-effects** a function may have. There is an effect that prevents impure functions from being part of query comprehensions.

Function types (in the context of this talk and slightly simplified):

$(T_1, \dots, T_n) \rightarrow T$  - pure, without side effects or recursion

$(T_1, \dots, T_n) \rightsquigarrow T$  - impure, may have side effects or recursion

```
fun impureFunction() {  
    print("hello");  
    3  
}  
  
# type function into REPL and then enter  
links> impureFunction;  
fun : () ~> Int
```

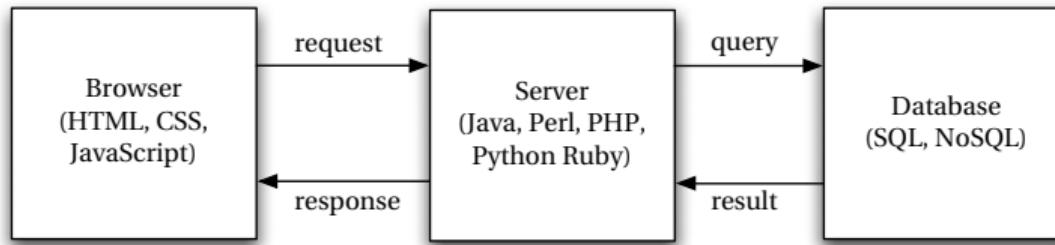
Links also supports user-defined effects through **effect handlers**, reflected in types

# Links: A **Tierless Web** Programming Language

# Tierless Web Programming

## Web application tiers

- Server
- Client (= Browser)
- Database

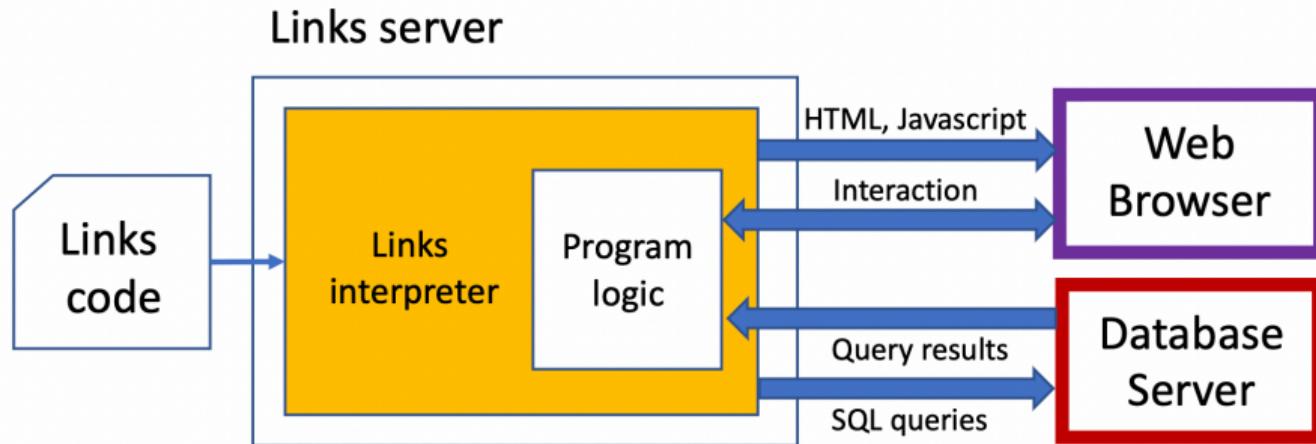


## Tierless web programming

- Single Links program contains application logic for all three tiers
- HTML fragments can be embedded directly
- Language-integrated database queries expressed using comprehension syntax

# Execution

Translation to SQL and JavaScript automatically performed by Links



Communication between server and client(s):

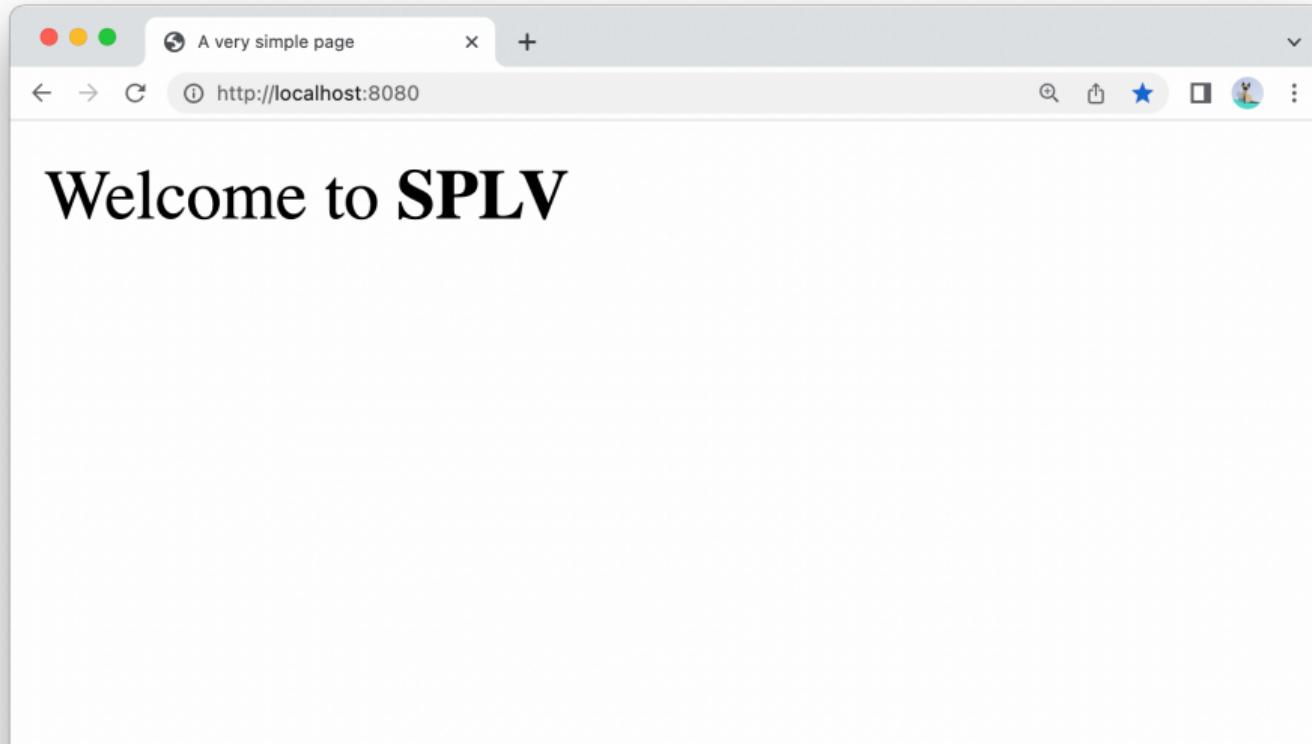
- Implicitly using remote procedure calls (RPCs)
- Explicitly by sending messages

## Serving a Very Simple Page

```
fun createPage(event) {  
    page  
    <html>  
        <title>A very simple page</title>  
        <body>  
            Welcome to {event}  
        </body>  
    </html>  
}  
  
addRoute("", fun(_) {createPage(<b>SPLV</b>)});  
servePages()
```

# A Very Simple Page

```
> linx --config=config simple.links
```



## Simple DOM Manipulations

Links provides builtin functions to manipulate DOM tree

```
sig addTaskToDom : (String) ~> ()  
fun addTaskToDom(task) client {  
    # Assumes that there is a <table> element  
    # with id "table"  
    var t = getNodeById ("table");  
    var new_row =  
        <tr><td>{stringToXml(task)}</td></tr>;  
    appendChildren (new_row , t)  
}
```

Note the annotation `client` on `addTaskToDom`!

# Locations

## Specification

- May annotate function  $f$  with location  $l \in \text{client}, \text{server}$
- “ $f$  only exists on  $l$ ”
- Functions without an annotation exist on both

## Behaviour

- Calling function not present on current location results in RPC
- Automatic (de)serialisation

## Constraints

- DOM manipulation only allowed on client
- Issuing database queries only allowed on server
- Not enforced by type system!

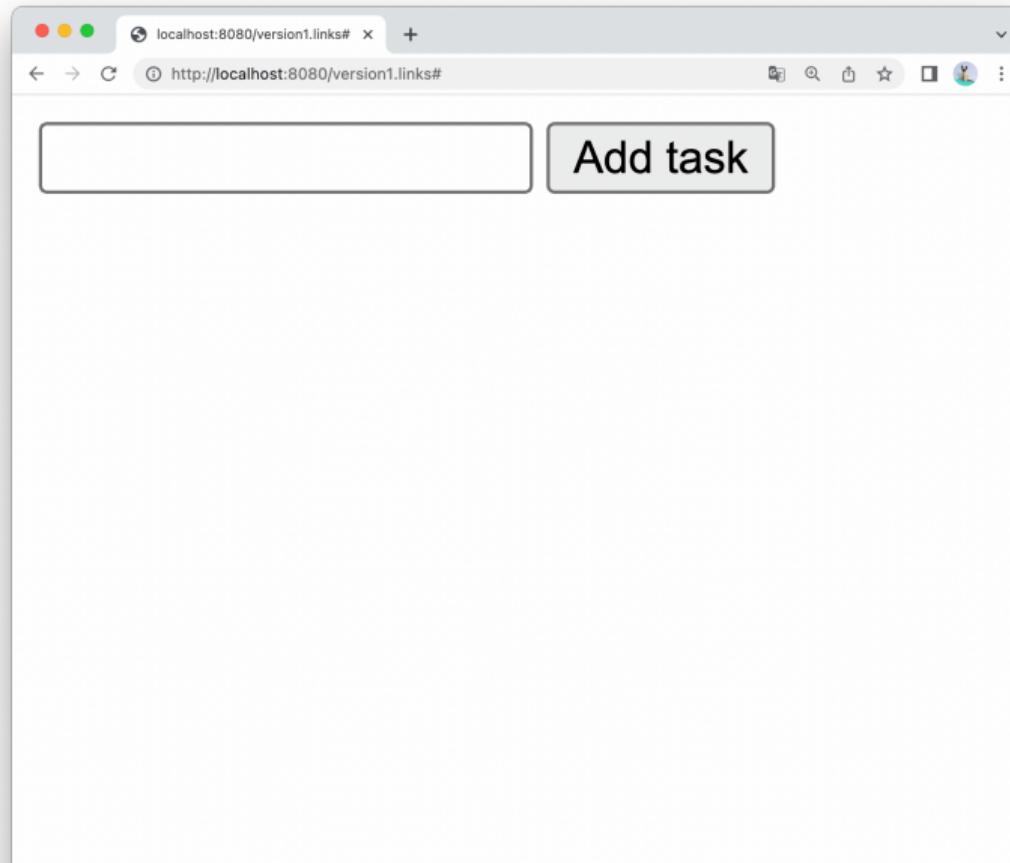
## Forms

```
fun createPage() {  
    page  
    <html><body>  
        <form l:onsubmit="{addTaskToDoList( task )}">  
            <input l:name="task" />  
            <button type="submit">Add task</button>  
        </form>  
        <table id="table"></table>  
    </body></html>  
}
```

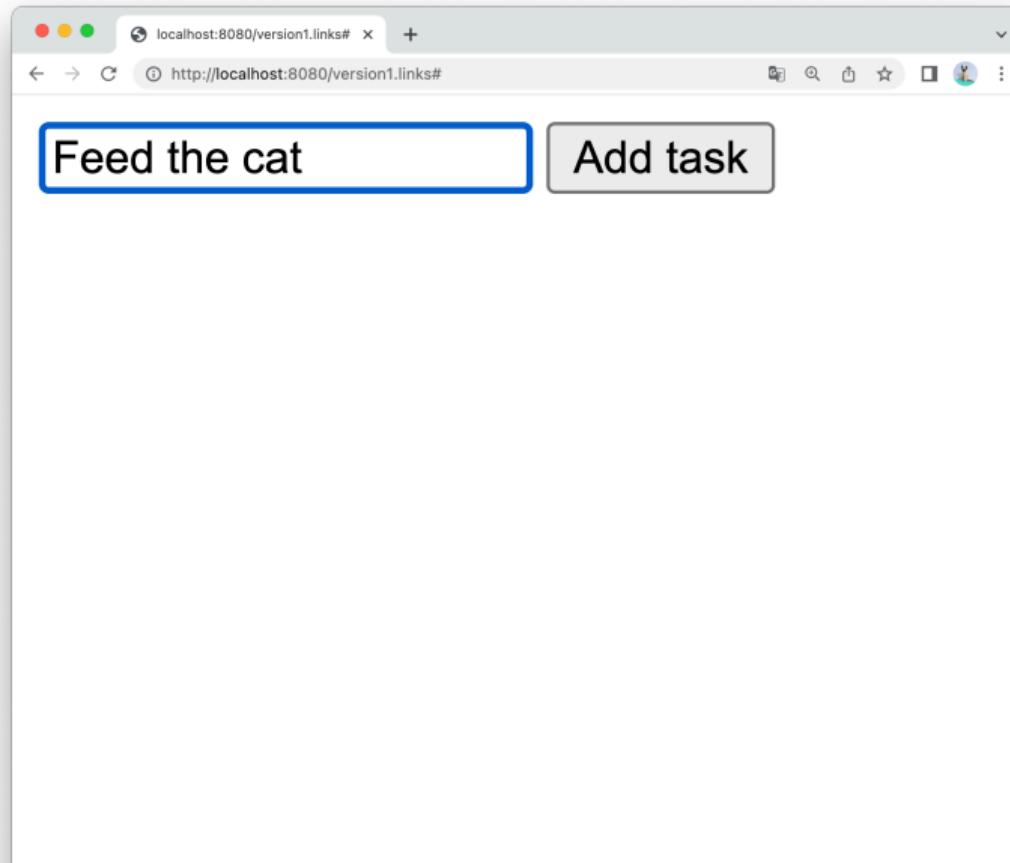
Simple mechanism for data input

- l:onsubmit handler expects expression of type unit
- task in scope!

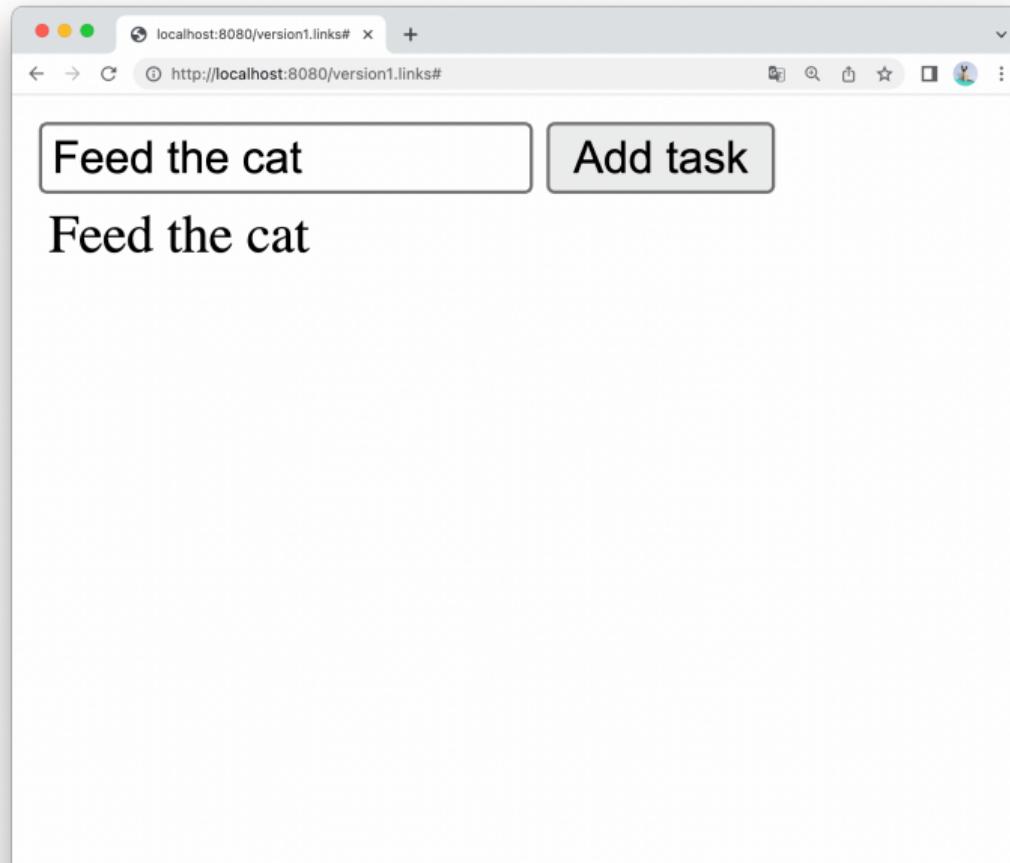
# A Simple Web App



# A Simple Web App



# A Simple Web App



# Managing State

## Previous example

- No explicit representation of program state, only implicitly in DOM tree
- Not suitable for real-world application

## Towards explicit state

```
typename Task = String;
typename State = [Task];

sig makeTable : (State) -> Xml # creates <table>
fun makeTable(tasks) {...}

sig makeBody : (State) ~> Xml # creates <body>
fun makeBody(tasks) {...}
```

## Full Example

```
sig makeTable : (State) -> Xml
fun makeTable(tasks) {...}

mutual {
    sig redraw : (State) ~> ()
    fun redraw(tasks) client {...}

    sig addTask : (State, Task) ~> ()
    fun addTask(tasks, task) {...}

    sig makeBody : (State) ~> Xml
    fun makeBody(tasks) {...}
}

fun createPage() {...}
```

# Full Example

```
sig makeTable : (State) -> Xml
fun makeTable(tasks) {...}

mutual {
    sig redraw : (State) ~> ()
    fun redraw(tasks) client {...}

    sig addTask : (State, Task) ~> ()
    fun addTask(tasks, task) {...}

    sig makeBody : (State) ~> Xml
    fun makeBody(tasks) {...}
}

fun createPage() {...}
```

## In detail:

```
fun createPage() {
    page
    <html>
        <body>
            { makeBody ([])}
        </body>
    </html>
}
```

# Full Example

```
sig makeTable : (State) -> Xml
fun makeTable(tasks) {...}

mutual {
    sig redraw : (State) ~> ()
    fun redraw(tasks) client {...}

    sig addTask : (State, Task) ~> ()
    fun addTask(tasks, task) {...}

    sig makeBody : (State) ~> Xml
    fun makeBody(tasks) {...}
}

fun createPage() {...}
```

## In detail:

```
fun makeBody(ts) {
    <body id="body">
        <form
            l:onsubmit="{addTask(ts, task)}">
            <input l:name="task"/>
            <button type="submit">
                Add task
            </button>
        </form>
        { makeTable(tasks)}
    </body>
}
```

# Full Example

```
sig makeTable : (State) -> Xml
fun makeTable(tasks) {...}

mutual {
    sig redraw : (State) ~> ()
    fun redraw(tasks) client {...}

    sig addTask : (State, Task) ~> ()
    fun addTask(tasks, task) {...}

    sig makeBody : (State) ~> Xml
    fun makeBody(tasks) {...}
}

fun createPage() {...}
```

## In detail:

```
fun makeTable(tasks) {
    <table id="table">
        { for (task <- tasks)
            <tr>
                <td>
                    {stringToXml(task)}
                </td>
            </tr>
        }
    </table>
}
```

# Full Example

```
sig makeTable : (State) -> Xml
fun makeTable(tasks) {...}

mutual {
    sig redraw : (State) ~> ()
    fun redraw(tasks) client {...}

    sig addTask : (State, Task) ~> ()
    fun addTask(tasks, task) {...}

    sig makeBody : (State) ~> Xml
    fun makeBody(tasks) {...}
}

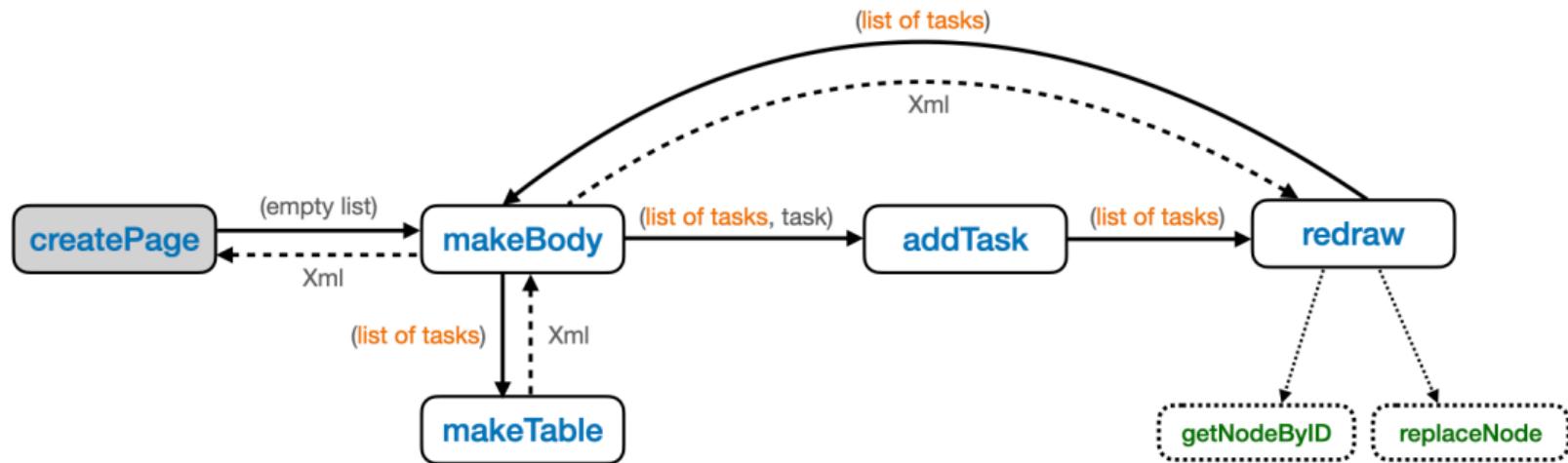
fun createPage() {...}
```

## In detail:

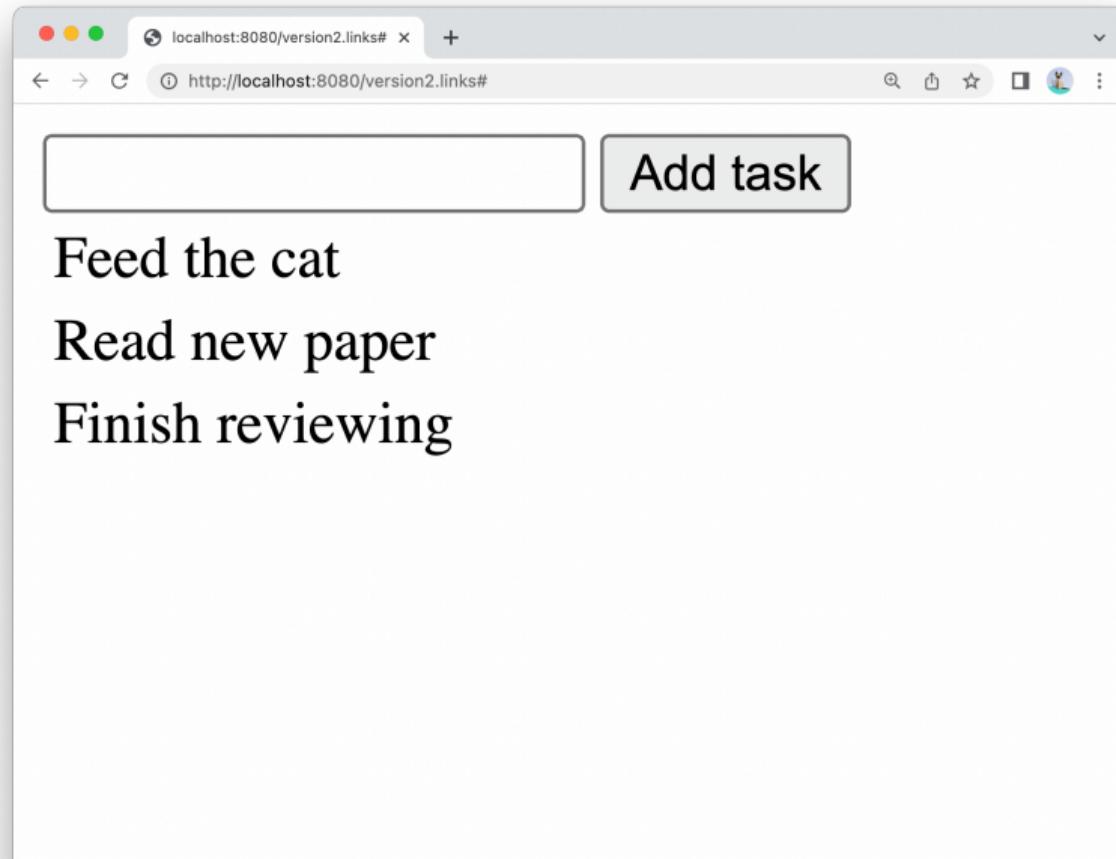
```
fun addTask(tasks, descr) {
    var new_tasks = tasks ++ [descr];
    redraw(new_tasks)
}

fun redraw(tasks) client {
    var old_body = getNodeById("body");
    var new_body = makeBody(tasks);
    replaceNode(new_body, old_body)
}
```

# A Simple Web App



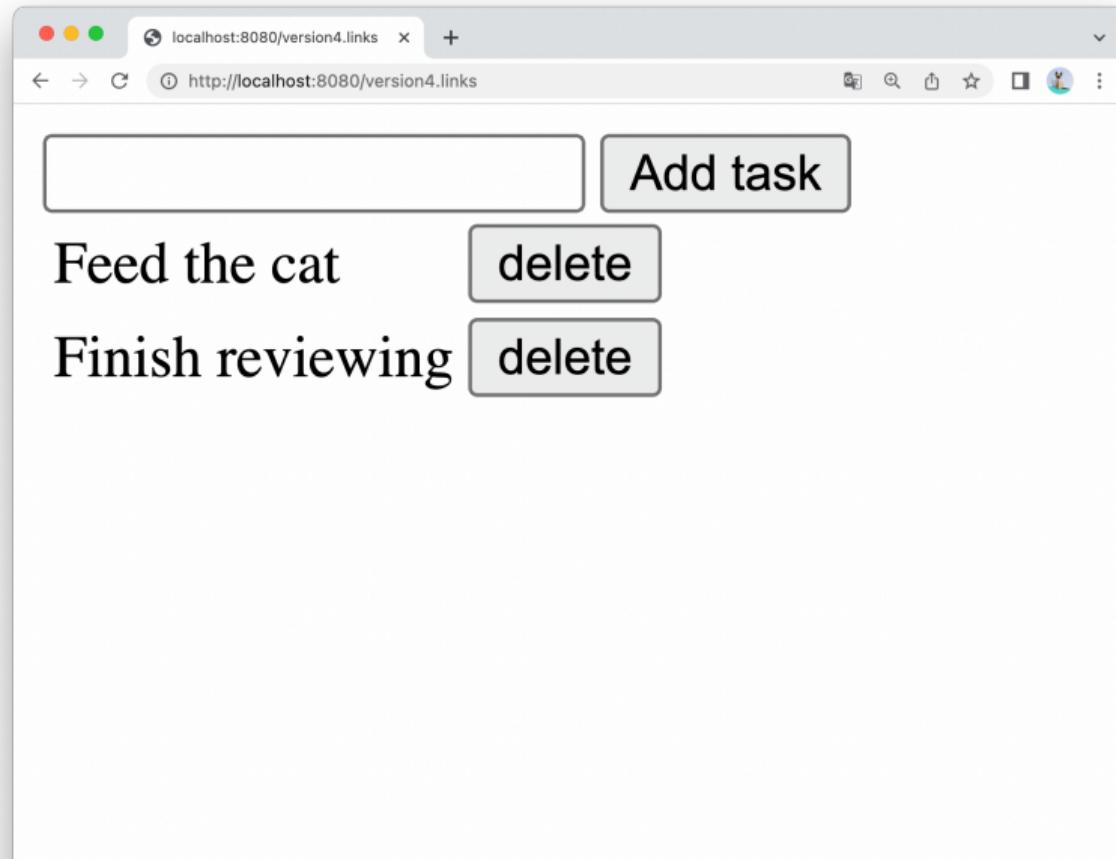
# A Simple Web App



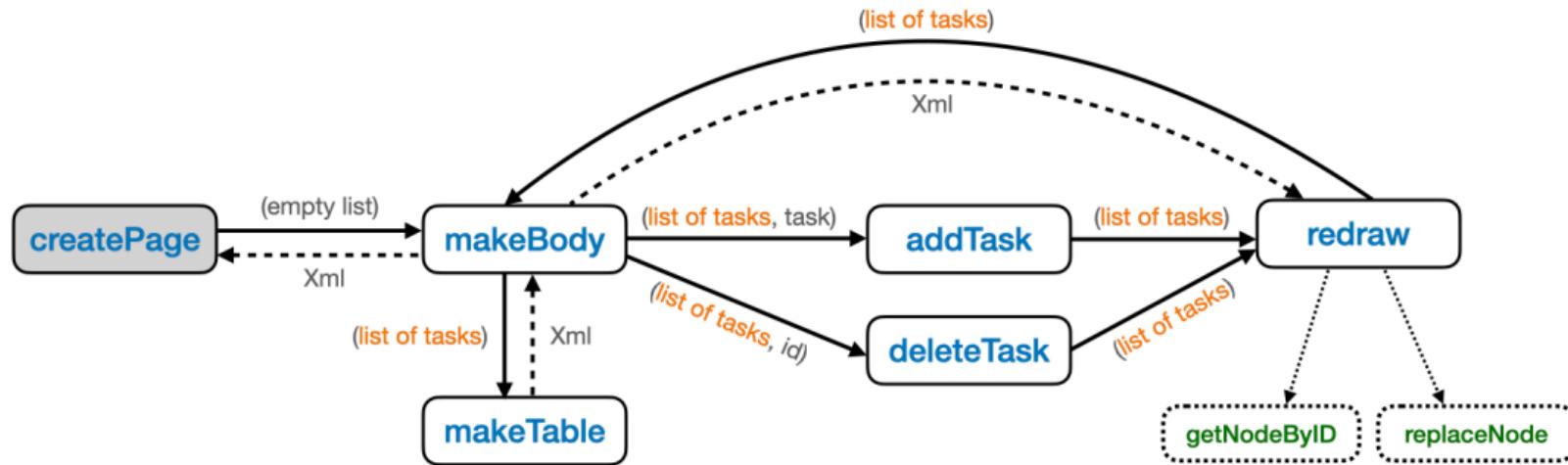
# Supporting Deletion

```
typename Task = (id: Int, descr: String);  
...  
fun deleteTask(tasks, delete_id) {  
    var new_tasks = filter(fun(t) t.id <> delete_id, tasks);  
    redraw(new_tasks)/  
}  
...  
fun makeTable(tasks) {  
    <table id="table">  
        { for (task <- tasks)  
            <tr>  
                ...  
                <td><button l:onclick="{ deleteTask (tasks, task.id)}" ... </td>  
            </tr>}  
    </table>  
}
```

# A Simple Web App



# A Simple Web App



## Persisting State

Language-integrated query: write DB queries in host language

- Static typechecking of queries and results
- Avoids security issues caused by building queries from strings
- Potential performance gains from combining queries (see GtoPdb implementation)

```
SELECT * FROM todo  
WHERE descr = 'Eat'
```

```
query { for (x <-- todo)  
        where (x.descr == "Eat")  
        [x] }
```

## DB Support for Example Application: Loading

```
var db = database "tasks.db";
var tasks_db = table "tasks" with (id : Int, descr : String) from db;

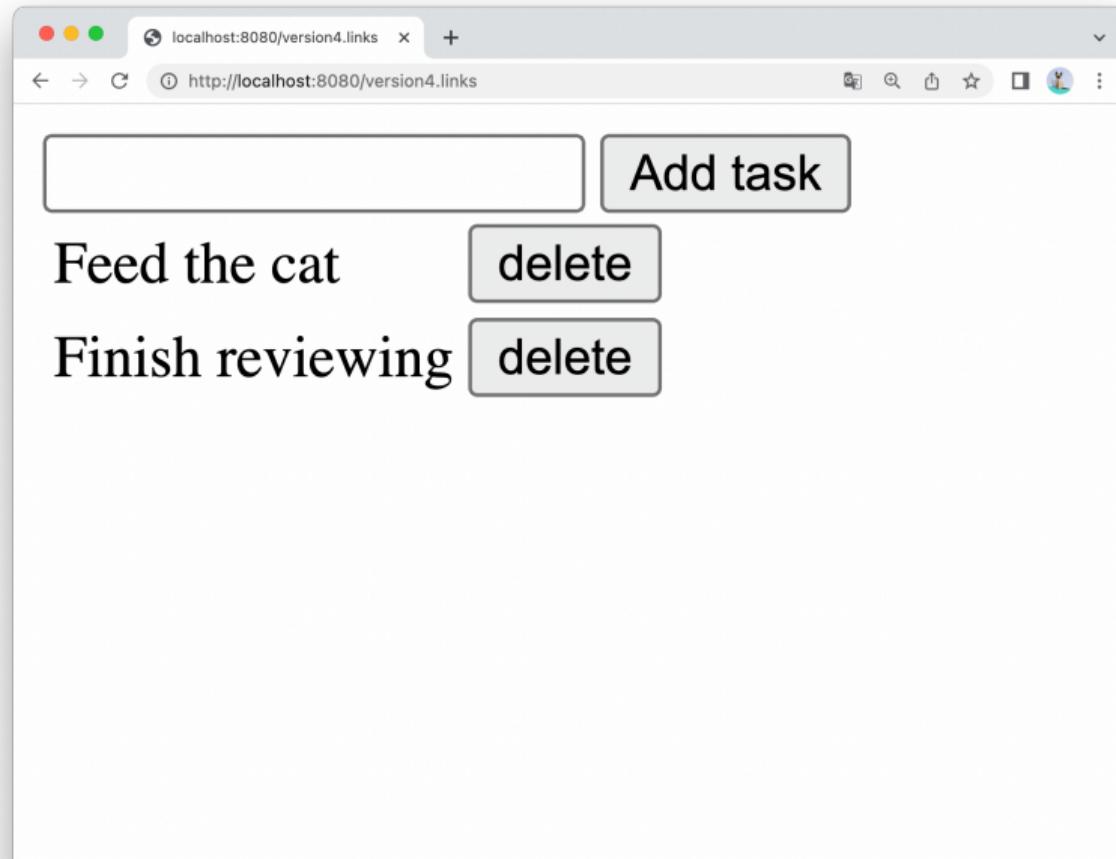
fun loadTasks() {
    query {for (task <-- tasks_db) [task] }
}

...
addRoute("", fun(_) {createPage(loadTasks())});
```

## DB Support for Example Application: Updating

```
...  
  
fun addTask(tasks, descr) server {  
    var id = maxId(tasks) + 1;  
    var new_task = (id=id, descr=descr);  
    insert (tasks_db) values [(id=new_task.id, descr=new_task.descr)];  
    var new_tasks = tasks ++ [new_task];  
    redraw(new_tasks)  
}  
  
fun deleteTask(tasks, delete_id) server {  
    var new_tasks = filter(fun(t) {t.id <> delete_id}, tasks);  
    delete (t <-> tasks_db) where (t.id == delete_id);  
    redraw(new_tasks)  
}
```

# A Simple Web App



# Pause for Reflection

## Issues with example application

- State manually passed around
- Manual modifications to DOM tree, overriding whole <body>
- Application logic, database access and presentation mixed

## More desirable solution

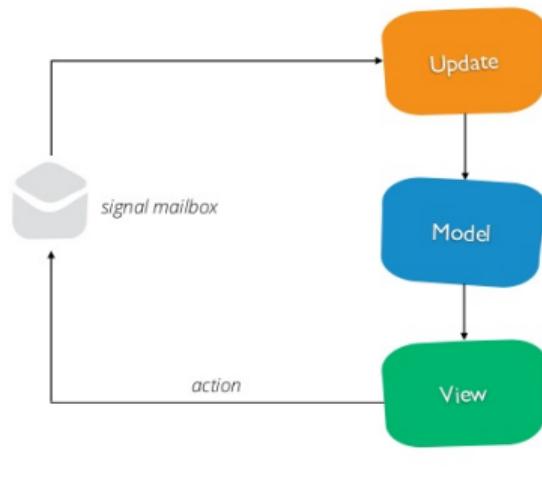
- Clear separation of state, logic for changing it, and presentation
- Perform database updates asynchronously

The building blocks (asynchronous processes, communication via messages) are present in Links...

... but so is a better solution!

# Model-View-Update

Approach towards design of interactive applications in functional style, originally introduced by Elm language



**Model:** State of application

**View:** Renders model as HTML

**Update:** Updates model based on UI messages

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Recently implemented in Links by Jake Browning and Simon Fowler

(MVU figure: <https://www.slideshare.net/RogerioChaves1/introduction-to-elm>)

# MVU framework

```
# Model-view-update (MVU) GUI paradigm: separating state from HTML rendering

open import Mvu; open import ...;                                # import MVU and other libraries

typename ...
typename Model = ( results: [ResultType], ... )                # define model and messages types
typename Messages = [| Continue | GetCat:String | ShowData | ... |];

fun ...                                                       # program logic

sig view : (Model) ~> HTML(Message)
fun view(model) {
    <functions to generate HTML and messages>
    <body includes calls to functions that access database>
}

sig updt : (Message, Model) {}~> Model                      # define a function to respond
fun updt(msg, model) {                                         # to messages
    switch(msg) {
        case Continue  -> redirect("/dataOverview"); model
        case GetCat(g) -> (model with displayCat=g)
        case ShowData  -> lookupData(model)
        case ... -> ...
    }
}
```

# Case study: The Guide to Pharmacology

# Curated Scientific Databases

## Curated Databases:

- “databases that are populated and updated with a great deal of human effort” (Buneman et al., 2008)
- Examples: CIA World Factbook, GtoPdb

## Curation challenges:

- Annotation propagation, provenance tracking, citation, archiving...
- Have to be hand-crafted for every curated DB — often with very stretched resources

**Goal: programming language support for curation functionality**

# GtoPdb: IUPHAR/BPS Guide to PHARMACOLOGY

Popular curated database detailing around 3000 pharmacological targets (e.g., receptors) and 12000 ligands (e.g., drugs)

Initially IUPHAR-DB, started in 2003

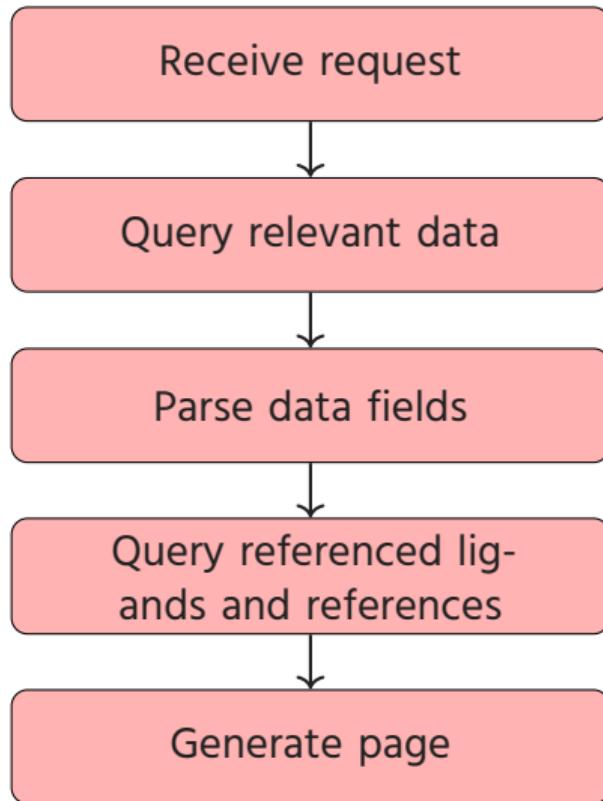
Manually updated by 2-3 full-time curation staff at UoE, on advice of subcommittees worldwide

Written in Java. Scale (as of late 2019):

- **89MB** (now 282MB) of data in **181 tables**
- **17935 lines** of data transformation code
- **28819 lines** of JSP rendering code
- **43129 lines** of data access code

The screenshot shows the homepage of the IUPHAR/BPS Guide to PHARMACOLOGY. At the top is a navigation bar with links for Home, About, Targets, Ligands, Diseases, Resources, Advanced search, Immuno Portal, and Malaria Portal. Below the navigation is a banner featuring a 3D molecular structure. The main content area has a section titled "What's new to Guide to PHARMACOLOGY" with a call to action to complete a survey. It also lists "New database version 2019.5 - released 13th November 2019" with several bullet points about updates. To the left is a "Quick links" sidebar with categories like Targets (G protein-coupled receptors, Ion channels, Nuclear hormone receptors, PTKs, Kinases, G proteic receptors, Transporters, Enzymes, Other protein targets), Ligands (Approved drugs, Synthetic organics, Metabolites, Natural products, Endogenous peptides, Other peptides, Nucleic acids, Antibodies, Labelled ligands), and Resources (Help documentation, FAQ, Tutorial, Download data & reports, REST web services). On the right is a sidebar for "GtoPdb" which links to the IUPHAR/MMV Guide to Malaria Pharmacology, featuring a logo of a brain-like structure with molecules. Another sidebar for "The Concise Guide to PHARMACOLOGY 2019/20" is also present.

# GtoPdb Page Lifecycle



Some substituted benzazepines such as SKF-83959 are G-protein biased agonists of the dopamine D<sub>1</sub> receptor and fail to activate  $\beta$ -arrestin recruitment [\[Reference id=28036\]](#); their ability to signal through G<sub>q</sub>-mediated pathways has been controversial [\[Reference id=33435\]](#).



Some substituted benzazepines such as SKF-83959 are G-protein biased agonists of the dopamine D<sub>1</sub> receptor and fail to activate  $\beta$ -arrestin recruitment [17]; their ability to signal through G<sub>q</sub>-mediated pathways has been controversial [32].

## Nested Queries

```
for ( l <-- ligand )
[( name = l.name,
  synonyms =
    for ( 12s <-- ligand2synonym )
      where ( 12s.ligand_id == l.ligand_id )
      [ 12s.synonym ]
)
[(name=L1,synonyms=[S1,S2]),(name=L2,synonyms=[]),...]
```

- Links queries can be nested (unlike SQL queries which are always flat)
- Query shredding technique provides a **static bound on query count**
- Nested queries are used **extensively** in GtoPdb, as shown earlier

# Reimplementation in Links

## Official GtoPdb

The screenshot shows the GtoPdb interface for the compound Beclometasone diphosphate (Ligand ID: 539). At the top, there's a navigation bar with links like Home, About, Targets, Ligands, Diseases, Resources, Advanced search, Immuno Portal, and Malaria Portal. Below the header is a banner for the IUPHAR/BPS Guide to PHARMACOLOGY. The main content area has a sub-header "Beclometasone diphosphate" and a detailed table of its properties. It includes a 2D chemical structure, calculated physico-chemical properties (Hydrogen bond acceptors: 7, Hydrogen bond donors: 1, Rotatable bonds: 8, Topological polar surface area: 106.97, Molecular weight: 520.22, XLogP: 2.83), and a table of Lipinski's rules violations (0). Below this is a "Structure and Physico-chemical Properties" section with tabs for 2D Structure, Calculated Physico-chemical Properties, and 3D Structure. Further down are sections for Summary, Biological activity, Clinical data, References, Structure, Similar ligands, and Immuno pharmacology. A "Classification" section provides details like Compound class (Synthetic organic), Approved drug? (Yes, IRMA-21076), Is prodrug? (Yes), and Active form (Beclometasone). The "IUPAC Name" section lists the full IUPAC name: (1R,3S,9aS,10S,11S,13S,14S,16S,17R)-9-chloro-11-hydroxy-10,13,16-trimethyl-3-oxo-17-(2-propenoyloxyacetyl)-6,7,8,11,12,14,15,16-octadecenoic acid(4-hydroxy-3-methoxy-2-propenyl ester).

## Links Reimplementation

The screenshot shows the Links reimplementation of the GtoPdb page for Beclometasone diphosphate (Ligand ID: 539). The layout is very similar to the original, with the IUPHAR/BPS Guide to PHARMACOLOGY banner at the top. The main content area includes a sub-header "Beclometasone diphosphate" and a detailed table of its properties. It features a 2D chemical structure, calculated physico-chemical properties (Hydrogen bond acceptors: 7, Hydrogen bond donors: 1, Rotatable bonds: 8, Topological polar surface area: 106.97, Molecular weight: 520.22781468, XLogP: 2.832), and a table of Lipinski's rules violations (0). Below this is a "Structure and Physico-chemical Properties" section with tabs for 2D Structure, Calculated Physico-chemical Properties, and 3D Structure. Further down are sections for Summary, Biological activity, Clinical data, References, Structure, Similar ligands, and Immuno pharmacology. A "Classification" section provides details like Compound class (Synthetic organic), Approved drug? (Yes, IRMA-21076), Is prodrug? (Yes), and Active form (Beclometasone). The "IUPAC Name" section lists the full IUPAC name: (1R,3S,9aS,10S,11S,13S,14S,16S,17R)-9-chloro-11-hydroxy-10,13,16-trimethyl-3-oxo-17-(2-propenoyloxyacetyl)-6,7,8,11,12,14,15,16-octadecenoic acid(4-hydroxy-3-methoxy-2-propenyl ester).

All major data pages reimplemented  
10981 lines of Links code, about 4 months of work  
**Underlying database unchanged**

# Evaluation

## Query count

- Number of queries performed per page load
- **Expectation:** Links lower due to static query bounds ✓

## Query handling time

- Time taken to execute query and process results into data structures
- **Expectation:** Either Links performs better due to fewer queries, or Java performs better due to faster marshalling ✓

## Page build time

- Time between request handler invocation and response being ready
- **Expectation:** Java to perform better due to JIT and maturity ✓

Performance measurements performed locally, using an instrumented Links interpreter and modified GtoPdb code. Sample of 150 random pages from object data and disease data pages.

# Ongoing Work: Curation Interface

Links GtoPdb Curation Home Targets Families Contributors Ligands Diseases Species References Projects

## Editing Disease with ID 1190

Basic Information

Disease ID:1190

Disease Name

Allergic rhinitis

Disease Description

A rhinitis that is an allergic inflammation and irritation of the nasal airways involving sneezing, runny nose, nasal congestion, itching and tearing of the eyes caused by exposure to an allergen such as pollen, dust, mold, animal dander and droppings of cockroaches or house dust mites.(DOID)

Database References

Add a crossreference

Database

Entrez Gene

Accession

Add Crossreference

Existing crossreferences

## Ongoing work: Curation interface

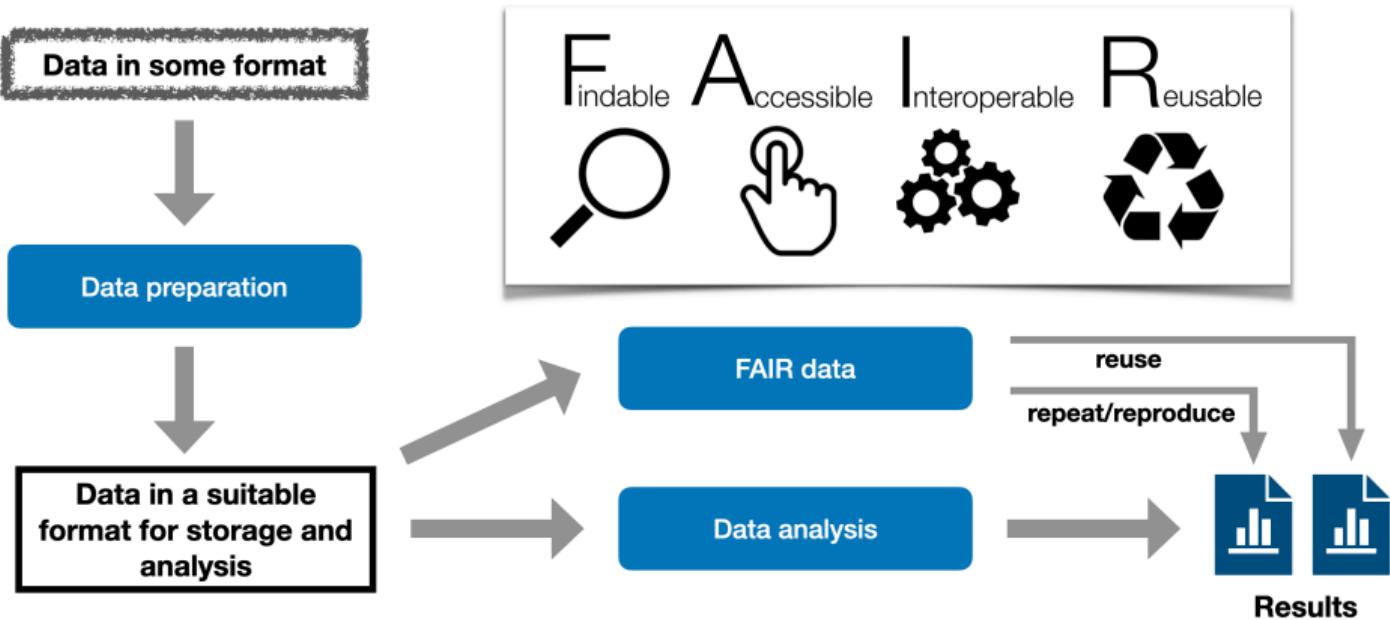
- Implemented two illustrative pages from curation interface
- Aim to use these as realistic case study for curation functionality

# Temporal case study: Covid 19 Data

# Scientific workflow



# FAIR Scientific workflow



# Making public data usable



[www.nrscotland.gov.uk/  
statistics-and-data](http://www.nrscotland.gov.uk/statistics-and-data)

Subcategories	Weeks
	Weekly Scottish Covid-19 fatality counts

CSV files

## Publicly available data

- Released weekly
- CSV files
- Columns are labelled with weeks
- Rows are labelled with subcategories
  - Category: Age
  - Subcategories: Under 1, 01-14, 15-44, 45-64, 65-74, 75-84, 85+

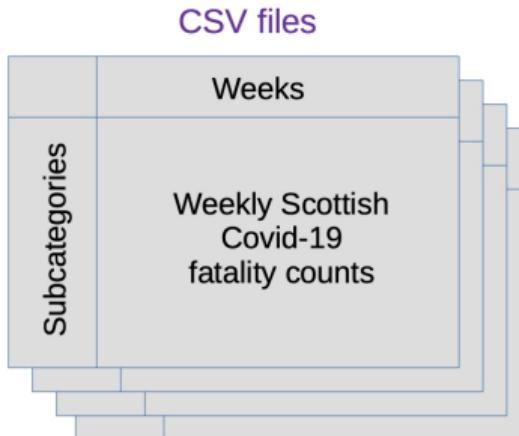
## Build a web-front end

- Use Links for rapid development

## Sample data

Table 1: Weekly ...							
Week number	1	...	11	12	13	...	
Week beginning	30-Dec-19	...	9-Mar-20	16-Mar-20	23-Mar-20	...	
Deaths	0	...	0	10	62	...	
Deaths - females	0	...	0	5	26	...	
Deaths - males	0	...	0	5	36	...	
	Deaths by age						
	Under 1 year	0	...	0	0	0	...
	01-14	0	...	0	0	0	...
	15-44	0	...	0	0	0	...
	45-64	0	...	0	1	12	...
	65-74	0	...	0	4	11	...
	85+	0	...	0	2	15	...
...	...	...	...	...	...	...	...

# CSV to relational database



[www.nrscotland.gov.uk/statistics-and-data](http://www.nrscotland.gov.uk/statistics-and-data)



Temporal database table

Week date	Sub-category	Fatality count	File_id

# Data comparison

Scottish Weekly COVID-19 Data Curation Interface    Overview    Query ▾    Pending    Upload    Other ▾

	16-03	23-03	30-03	06-04	13-04	20-04	27-04
Under 1 year	0	0	0	0	0	0	0
% incr	-	-	-	-	-	-	-
01-14	0	0	0	0	0	0	0
% incr	-	-	-	-	-	-	-
15-44	0	0	4	4	2	7	2
% incr	-	-	-	0.0	-50.0	250.0	-71.4
45-64	1	12	30	64	46	53	38
% incr	-	1100.0	150.0	113.3	-28.1	15.2	-28.3
65-74	4	11	67	101	81	97	73
% incr	-	175.0	509.0	50.7	-19.8	19.7	-24.7
75-84	3	24	107	228	223	225	142
% incr	-	700.0	345.8	113.0	-2.1	0.8	-36.8

# Data contains updates!

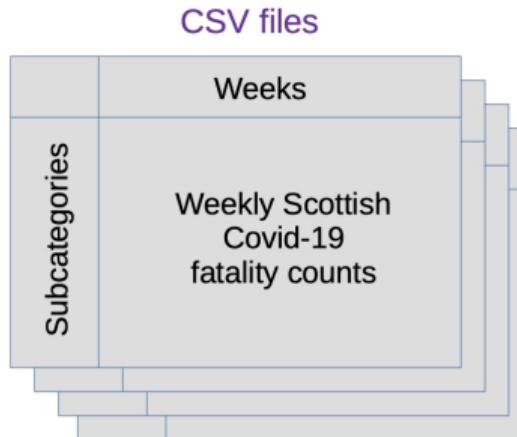
New data from the CSV of 30-Mar-2020

	A	N	O	P
3	Week number	12	13	14
4	Week beginning	16-Mar-20	23-Mar-20	30-Mar-20
5				
6				
7	Deaths involving COVID-19	10	62	282
8	Deaths involving COVID-19 - females	5	26	126
9	Deaths involving COVID-19 - males	5	36	156

Updates from the CSV of 13-Apr-2020

	A	N	O	P	Q	R	16
3	Week number	12	13	14	15	16	
4	Week beginning	16-Mar-20	23-Mar-20	30-Mar-20	6-Apr-20	13-Apr-20	
5							
6							
7	Deaths involving COVID-19	10	62	283	610	651	
8	Deaths involving COVID-19 - females	5	26	127	262	308	
9	Deaths involving COVID-19 - males	5	36	156	348	343	

# CSV to temporal relational database



Temporal database table

Week date	Sub-category	Fatality count	File_id	Date_valid_from	Date_valid_to

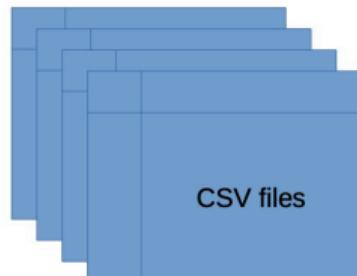
# Asking different questions



How many deaths  
were reported in  
the week of 5 July?



How were those  
deaths distributed  
across the health  
boards?



How many  
deaths were first  
reported in  
week of July 5?



How does that  
differ from the  
most recently  
reported figure?

Which health  
boards reported the  
most changes?

# Links app screenshot: item provenance

The screenshot shows a web browser window titled "Scottish COVID-19 Data Curati" with the URL "http://localhost:8080/provQuery#top". The main content area is titled "Provenance: individual data items" and displays a table of data item update history. Below the table are two buttons: "See modifications in context" and "Continue". A second section at the bottom shows a table of data items with at least one accepted/rejected modification, with a "See history" button.

Scottish Weekly COVID-19 Data Curation Interface   Overview   Query ▾   Pending   Upload   Other ▾

Provenance: individual data items

Data item update history

The current value for subcategory **Female** and week **2020-03-30** is **127**.  
This data item has the following history.

Date	Value	Decision	Week of modification
2022-11-21 20:18:12+0	126	New data item stored	2020-03-30
2022-11-21 20:18:39+0	127	Modification accepted	2020-04-13

See modifications in context   Continue

Data items with at least one accepted/rejected modification

Week	Category	Subcategory	Number of updates seen
2020-03-30	All	All	2 (all accepted)

See history

# Links app screenshot: week provenance

The screenshot shows a web browser window for the "Scottish COVID-19 Data Curati" application, specifically the "provWeeks" page at <http://localhost:8080/provWeeks>. The interface is titled "Scottish Weekly COVID-19 Data Curation Interface".

**Week 2020-04-13**

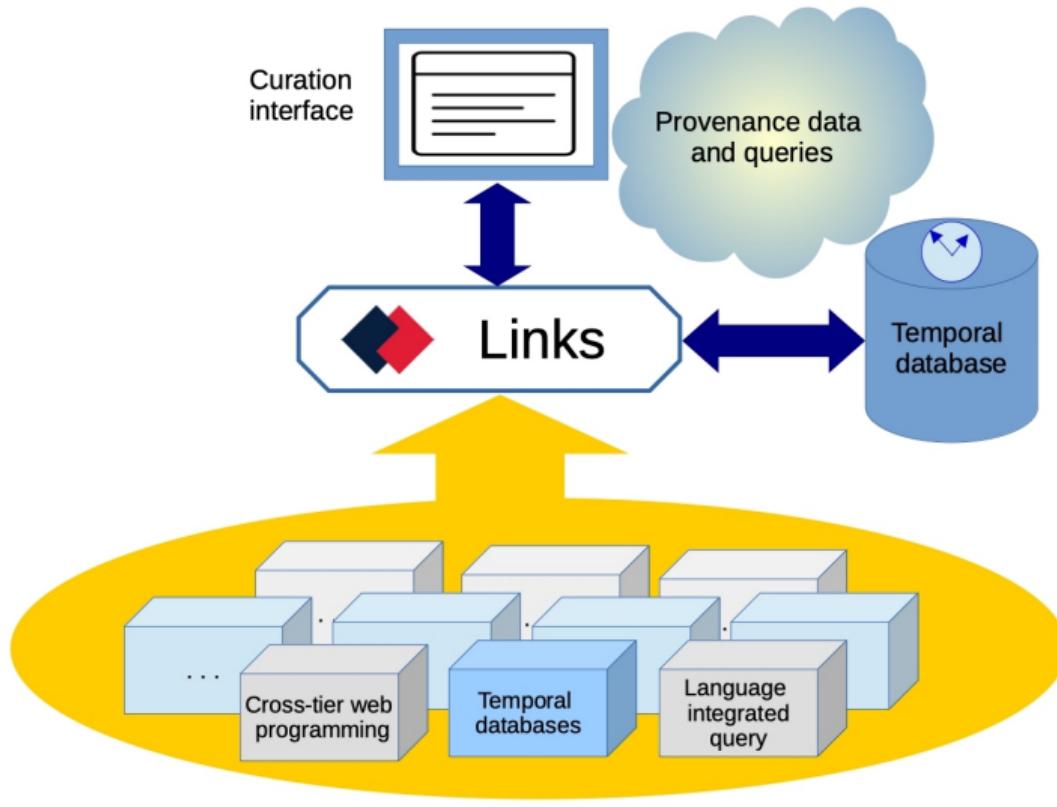
For this week, there are **74** data items, added in the week of 2020-04-13. In total, there have been **16** accepted updates and **9** rejected updates. This week has the following update history.

Week of modification	Accepted updates	Rejected updates
2020-04-20	16	0
2020-04-27	0	9

[Hide details](#)

Week of modification	Category	Subcategory	Decision	
2020-04-20	All	All	Accepted	<a href="#">See history</a>
2020-04-20	Sex	Female	Accepted	<a href="#">See history</a>
2020-04-20	Sex	Male	Accepted	<a href="#">See history</a>
2020-04-20	Age	65-74	Accepted	<a href="#">See history</a>

# Using Links to build curation interfaces



# Temporal Databases

## Temporal features in SQL:2011

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### ABSTRACT

SQL:2011 was published in December of 2011, replacing SQL:2008 as the most recent revision of the SQL standard. This paper covers the most important new functionality that is part of SQL:2011: the ability to create and manipulate temporal tables.

### 1. Introduction

SQL is the predominant database query language standard published jointly by ISO (the International Organization for Standardization) and IEC (the International Electrotechnical Commission). In December 2011, ISO/IEC published the latest edition of the SQL standard, SQL:2011. A recent article in *SIGMOD Record* provides a brief survey of the new features in SQL:2011 [1]. Because of space constraints, it did not cover the most important new feature in SQL:2011: the ability to create and manipulate temporal tables, i.e., tables whose rows are associated with one or more temporal periods. This is the subject of the current article.

### 2. Temporal data support

Extensions to support temporal data<sup>1</sup> in SQL have long been desired. There is a large body of research papers, conference publications, and books on this topic, some dating back to the early 1980s. For more details, we refer the readers to an extensive (but outdated) bibliography [2] and to books such as [3] and [4].

Though the previous academic research produced a large number of solutions, the commercial adoption has been rather slow. It is only recently that commercial database management systems (DBMSs) have begun to offer SQL extensions for managing temporal data [5, 6, 7]. Prior to this development, users were forced to

implement temporal support as part of the application logic, which often results in long and error-prone development cycles and complex, hard-to-maintain code.

In 1995, the ISO SQL committee initiated a project to create a new part of SQL standard devoted to the language extensions for the temporal data support. A set of language extensions based on (but not identical to) TSQL2 [8] were submitted for standardization at that time. Unfortunately, these proposals generated considerable controversy (see [9] for more details), and failed to get adequate support from the ISO SQL committee's membership. In addition, there was no indication that key DBMS vendors were planning to implement these extensions in their products. Eventually, the work on this new part was cancelled in 2001.

Recently, a new set of language extensions for temporal data support were submitted to and accepted by the ISO SQL committee. These language extensions are now part of SQL:2011 Part 2, SQL-Temporal [10], instead of appearing as a new part. There is currently at least one commercial implementation [5] based on these extensions that the authors are aware of.

#### 2.1 Periods

The cornerstone of temporal data support in SQL:2011 is the ability to define and associate time periods with the rows of a table. Essentially, a time period is a mathematical interval on the timeline, demarcated by a start time and an end time.

Many treatments of temporal databases introduce a period data type, defined as an ordered pair of two datetime values, for the purpose of associating time periods with the rows of a table. SQL:2011 has not taken this route. Adding a new data type to the SQL standard (or to an SQL product) is a costly venture because of the need to support the new data type in the tools and other software packages that form the ecosystem surrounding SQL. For example, if a period type were added to SQL, then it would have to also be added to the stored procedure language, to all database APIs such as JDBC, ODBC, and .NET, as well as to the surrounding technology such as ETL products, replication servers, and so on. It would also be some challenge of communicating period values to host languages that do not support period as a native data type, such as C or Java. These factors can potentially slow down the adoption of new type for a long time.

**SQL:2011 standardises SQL temporal extensions, but these are **not widely implemented****

**Thus, users must implement temporal support themselves: brittle, error-prone**

1. Note that there is no single, commonly accepted definition of the term "temporal data". For the purposes of this article, we define "temporal data" to mean any data with one or more associated time periods during which that data is deemed to be effective or valid along some time dimension.

# Developing Time-Oriented Database Applications in SQL

RICHARD T. SNODGRASS

---



Morgan Kaufmann Publishers  
San Francisco, California

# Dimensions of Time

## User-defined time

- Single field (for example, date of birth). Uninteresting for our purposes.

## Transaction time

- The time rows were present in the database.

## Valid time

- The time a row was valid in the domain being modelled.

## (Bitemporal)

- Transaction time and valid time used together.

# Transaction-time: tracking database changes

## Transaction time tables model when a fact was stored in a database.

- Modification operations manipulate ‘recorded from’ and ‘recorded to’ fields.
- Users do **not** modify the ‘recorded from’ and ‘recorded to’ fields directly.
- Timestamps refer only to the **past**.
- Database grows monotonically: data never lost.

- Go shopping
- Cook dinner
- Walk the dog
- Watch TV

task	done	from	to
Go shopping	t	11:00	$\infty$
Cook dinner	f	11:00	$\infty$
Walk the dog	f	11:00	$\infty$
Watch TV	f	11:00	$\infty$

# Transaction Time Modifications

Check off “cook dinner”

- Go shopping
- Cook dinner
- Walk the dog
- Watch TV

```
update ( x <-t- todoTbl)
  where (ttData(x).task == "Cook dinner")
    set (done = true)
```

task	done	from	to
Go shopping	t	11:00	$\infty$
Cook dinner	f	11:00	17:30
Walk the dog	f	11:00	$\infty$
Watch TV	f	11:00	$\infty$
Cook dinner	t	17:30	$\infty$

# Transaction Time Modifications

...then delete "Watch TV"

- Go shopping
- Cook dinner
- Walk the dog

```
delete (x <-t- todoTbl)
       where (ttData(x).task == "Watch TV")
```

task	done	from	to
Go shopping	t	11:00	$\infty$
Cook dinner	f	11:00	17:30
Walk the dog	f	11:00	$\infty$
Watch TV	f	11:00	19:00
Cook dinner	t	17:30	$\infty$

# Transaction Time Queries

What was the state of the to-do list at 18:00?

```
query { for (x <-t- todoTbl)
  where ((time >= ttFrom(x)) && (time < ttTo(x)))
  [ttData(x)]};
```

or equivalently

```
query nested { for (x <- ttAt(todoTbl, time)) [x]}
```

task	done
Go shopping	t
Cook dinner	t
Walk the dog	f
Go shopping	f

## Transaction Time Queries

When was it recorded that “Cook dinner” was completed?

```
query { for (x <-t- todoTbl)
  where ((ttData(x).task=="Cook dinner")
    && (ttData(x).done==true))
  [(time=ttFrom(x))];
```

time
17:30

## Transaction Time Queries

Give the change history for task "Cook dinner".

```
query { for (x <-t- todoTbl)
  where (ttData(x).task=="Cook dinner")
    [(task=ttData(x).task,done=ttData(x).done,
      tt_from=ttFrom(x),tt_to=ttTo(x))];
```

task	done	tt_from	tt_to
Cook dinner	f	11:00	17:30
Cook dinner	t	17:30	$\infty$

# Valid Time Tables

## Valid-time: tracking real-world changes

**Valid time tables model when a fact was true in the modelled reality.**

- Timestamps can refer to **future** as well as past
- Users **can** manipulate 'valid from' and 'valid to' fields directly (for example, extending an employment contract)
- Ability to apply an update or deletion over a time period: **sequenced** updates

Name	Position	Salary	from	to
Alice	Lecturer	£40000	2000	2008
Alice	Senior Lecturer	£50000	2008	$\infty$
Bob	PhD Student	£15000	2019	2023

## Valid Time Modifications

Name	Position	Salary	from	to
Alice	Lecturer	£40000	2000	2008
Alice	Senior Lecturer	£50000	2008	$\infty$
Bob	PhD Student	£15000	2019	2023
Carol	Professor	£70000	2022	$\infty$

Hire Carol as a professor, on a permanent contract.  
**(Current insert)**

```
insert employees values (Name = "Carol", Position = "Professor", Salary = 70000)
```

## Valid Time Modifications

Name	Position	Salary	from	to
Alice	Lecturer	£40000	2000	2008
Alice	Senior Lecturer	£50000	2008	2022
Bob	PhD Student	£15000	2019	2023
Carol	Professor	£70000	2022	$\infty$

Alice has resigned.  
**(Current deletion)**

```
delete (x ← employees) where x.name == "Alice"
```

## Valid Time Modifications

Name	Position	Salary	from	to
Alice	Lecturer	£40000	2000	2008
Alice	Senior Lecturer	£50000	2008	2022
Bob	PhD Student	£15000	2019	2023
Carol	Professor	£70000	2022	2023
Carol	Head of School	£70000	2023	2026
Carol	Professor	£70000	2026	$\infty$

Carol will be Head of School between 2023 and 2026.  
**(Sequenced Update)**

```
update (x ← employees)
between (2023, 2026)
where (x.name == "Carol")
set (position = "Head of School")
```

# Valid Time Modifications

Name	Position	Salary	from	to
Alice	Lecturer	£40000	2000	2008
Alice	Senior Lecturer	£50000	2008	2020
Bob	PhD Student	£15000	2019	2024
Carol	Professor	£70000	2022	2023
Carol	Head of School	£70000	2023	2026
Carol	Professor	£70000	2026	$\infty$

Extend Bob's contract until 2024.  
**(Nonsequenced Update)**

```
update nonsequenced (x ← employees)
  where ((data x).name == "Bob")
    set (x valid to 2024)
```

# Formalism

## Key idea

Define direct semantics for temporal operations, and show translations into non-temporal DB-supporting  $\lambda$ -calculus

$$M \Downarrow_{\Delta, \iota}^T (V, \Delta')$$

Evaluate term  $M$  wrt. database  $\Delta$  at timestamp  $\iota$ , resulting in value  $V$  and updated database  $\Delta'$

## Formalism Example ( $\lambda_{\text{TLINQ}}$ update)

$$L \Downarrow_{\Delta, \iota}^T (t, \Delta_1) \quad \Delta_2 = \Delta_1 [t \mapsto \hat{\bigcup} \{ \text{upd}(v) \mid v \in \Delta_1(t) \}]$$

$\text{upd}(\text{data}^{[\text{start}, \text{end}]}) =$

$$\begin{cases} \{ \text{data}^{[\text{start}, \iota]}, (\text{data with } \overrightarrow{\ell = V})^{[\iota, \infty)} \} \\ \text{if } M\{\text{data}/x\} \Downarrow_{\iota}^* \text{true}, (N_i\{\text{data}/x\} \Downarrow_{\iota}^* V_i)_i, \text{ and end} = \infty \\ \{ \text{data}^{[\text{start}, \text{end}]} \} \quad \text{otherwise} \end{cases}$$

---

$$\text{update } (x \Leftarrow L) \text{ where } M \text{ set } (\overrightarrow{\ell = N}) \Downarrow_{\Delta, \iota}^T (( ), \Delta_2)$$

For every record where the predicate matches, close off existing row and add updated row (valid from now until forever)

# Formalism Example (Translation)

```
[[update(ℓi:Ai)i ∈ I (x ⇐ L) where M set (ℓ = Nj)j ∈ J]] =  
let tbl = [[L]] in  
let affected = query  
for (x ← get tbl)  
    where ((restrict(x, {ℓi}i ∈ I, [[M]]) ∧ isCurrent(x)))  
        ⎧ (ℓi = x.ℓi)i ∈ I/J ⊕  
        ⎨ (ℓj = restrict(x, {ℓi}i ∈ I, [[Nj]])j ∈ J ⊕  
        ⎩ (start = now, end = ∞)  
in  
update (x ⇐ tbl)  
    where (restrict(x,  $\overrightarrow{\ell}$ , [[M]]) ∧ isCurrent(x))  
    set (end = now);  
insert tbl values affected
```

- Calculate set of affected rows (query)
- Close off existing rows (update)
- Insert affected rows (insert)
  
- (restrict used to  $\eta$ -expand translated record to ensure type correctness)

# Metatheory ( $\lambda_{\text{TLINQ}}$ )

## Preservation

- A well-typed closed term evaluated wrt. a well-formed database will always evaluate to a value paired with another well-formed database

## Semantics Preservation

- The translation of a well-typed, closed  $\lambda_{\text{TLINQ}}$  term and well-formed database will evaluate to a value and database corresponding to the result of evaluating using the native semantics

Similar results hold for  $\lambda_{\text{VLINQ}}$

# Sequenced Joins

## Joining with a nontemporal table

name	band	from	to
Alice	A08	2000	2008
Alice	A09	2008	2020
Bob	B01	2019	2024

band	salary
B01	£15000
A07	£33000
A08	£40000
A09	£50000
UE10	£70000

Pair names of employees with their salaries

name	salary	from	to
Alice	£40000	2000	2008
Alice	£50000	2008	2020
Bob	£15000	2019	2024

## Joining with a temporal table

name	band	from	to
Alice	A08	2000	2008
Alice	A09	2008	2020
Bob	B01	2019	2024

band	salary	from	to
B01	£15000	2000	2015
A07	£33000	2000	2015
A08	£40000	2000	2015
A09	£50000	2000	2015
B01	£16000	2015	$\infty$
A07	£34000	2015	$\infty$
A08	£41000	2015	$\infty$
A09	£51000	2015	$\infty$

Pair names of employees with their salaries at each point in time

## Joining with a temporal table

name	band	from	to
Alice	A08	2000	2008
Alice	A09	2008	2020
Bob	B01	2019	2024

band	salary	from	to
B01	£15000	2000	2015
A07	£33000	2000	2015
A08	£40000	2000	2015
A09	£50000	2000	2015
B01	£16000	2015	$\infty$
A07	£34000	2015	$\infty$
A08	£41000	2015	$\infty$
A09	£51000	2015	$\infty$

Pair names of employees with their salaries at each point in time

name	salary	from	to
Alice	£40000	2000	2008
Alice	£50000	2008	2015
Alice	£51000	2015	2020
Bob	£16000	2019	2024

## Joining with a temporal table

name	band	from	to
Alice	A08	2000	2008
Alice	A09	2008	2020
Bob	B01	2019	2024

band	salary	from	to
B01	£15000	2000	2015
A07	£33000	2000	2015
A08	£40000	2000	2015
A09	£50000	2000	2015
B01	£16000	2015	$\infty$
A07	£34000	2015	$\infty$
A08	£41000	2015	$\infty$
A09	£51000	2015	$\infty$

Pair names of employees with their salaries at each point in time

- Straightforward to encode for flat queries using LINQ
- Simple rewrite using greatest and least functions to calculate the intersections of the periods of validity

# Temporal case study: XML documents

# Temporal case study: XML documents

## A different context

- NPL (National Physical Laboratory) is Britain's National Metrology Institute
- Measuring devices require calibration certificates that provide traceability back to SI units
- The digital transformation of metrology is ongoing: recent XML schema for digital calibration certificates

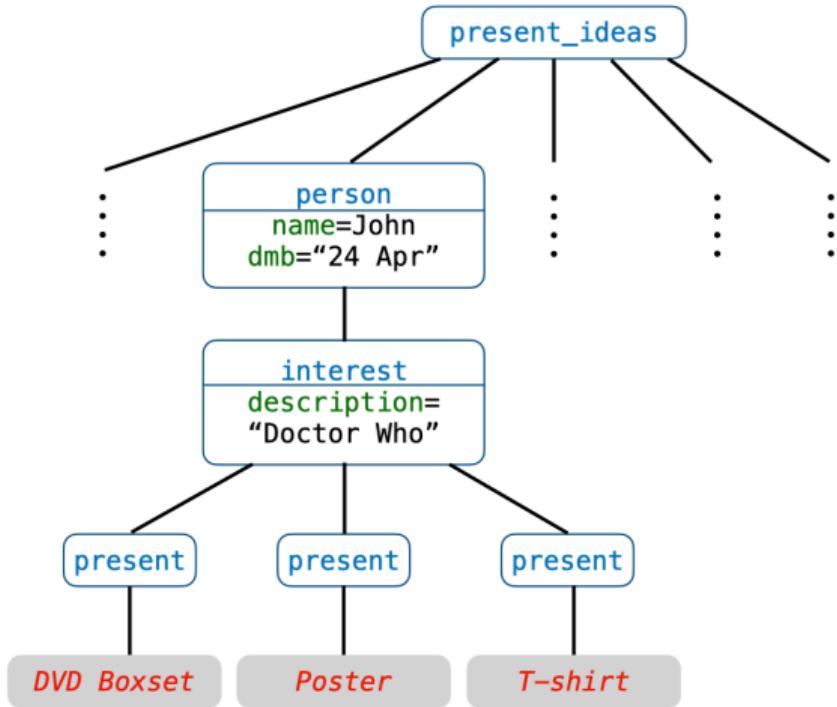
## Research project

- How can Links with temporal features be applied in this domain?
- Prototype curation interface developed for XML documents
- Well-received at metrology conference last year
- Recent funding to develop this further

## Demo

# XML: Extensible Markup Language

```
<present_ideas>  
  <person name="John" dmb="24 Apr"/>  
  <person name="Fred" dmb="03 Jun">  
    <interest description = "Doctor Who">  
      <present>DVD Boxset</present>  
      <present>Poster</present>  
      <present>T-shirt</present>  
    </interest>  
  </person>  
  <person name="Amina" dmb="04 Jun"/>  
  <person name="Kim" dmb="10 Sep">  
    <present>Voucher</present>  
  <person name="May" dmb="25 Dec"/>  
</present_ideas>
```



# Implementation choices

## Links: relational database

- 1. Use XML schema to determine database tables
- 2. Use a schema-agnostic approach to store XML ✓

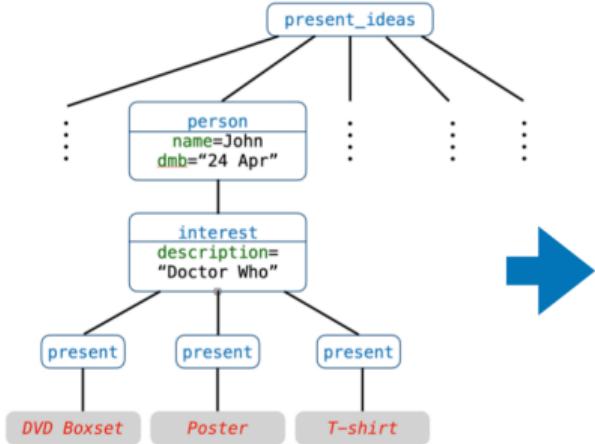
## Dynamic Dewey labelling [Xu et al (SIGMOD 2009)]

- Comparison of labels to determine relationship between nodes
- Unique label for each node and efficient for querying
- No relabelling needed for insertion so more efficient than others
- Straightforward to implement

## Evaluation

- User interface could be useful for people who don't know XML
- Schema-agnosticism was the right choice because the schema is not final

# XML labelling for relational storage



xml\_node

Label	Tag	Text	...
+001	present_ideas		
+001.+002	person		
+001.+002.+003	interest		
+001.+002.+003.+002	present		
+001.+002.+003.+002.+001		DVD Boxset	

xml\_attr

Label	Attr	Value	...
+001.+002	name	John	
+001.+002	dmb	24 Apr	
+001.+002.+003	description	Doctor Who	

# Demo

# Wrapping up

# How to install Links

## Using opam 4.14.1

```
> opam switch create 4.14.1  
> eval $(opam env --switch=4.14.1); opam switch 4.14.1  
> opam install links
```

Install database driver: links-postgresql or links-sqlite3

Database instructions for PostgreSQL:

<https://github.com/links-lang/links/wiki/Database-setup>

## Database and opam installation for macOS

Install HomeBrew: <https://brew.sh>

```
> brew install opam
```

Install database with brew: postgresql or sqlite3

These instructions were correct as of 24 July 2023 but may now be out-of-date. See <https://github.com/links-lang> for current instructions.

# Resources

## Software

- The Links Programming Language: <https://links-lang.org>

## Case Studies

- Covid 19 data: <https://doi.org/10.5281/zenodo.7199221>
- XML documents: <https://doi.org/10.5281/zenodo.7551691>

## Tutorial material

- Slides and tutorial code:  
[https://github.com/links-lang/splv2023\\_example\\_code](https://github.com/links-lang/splv2023_example_code)

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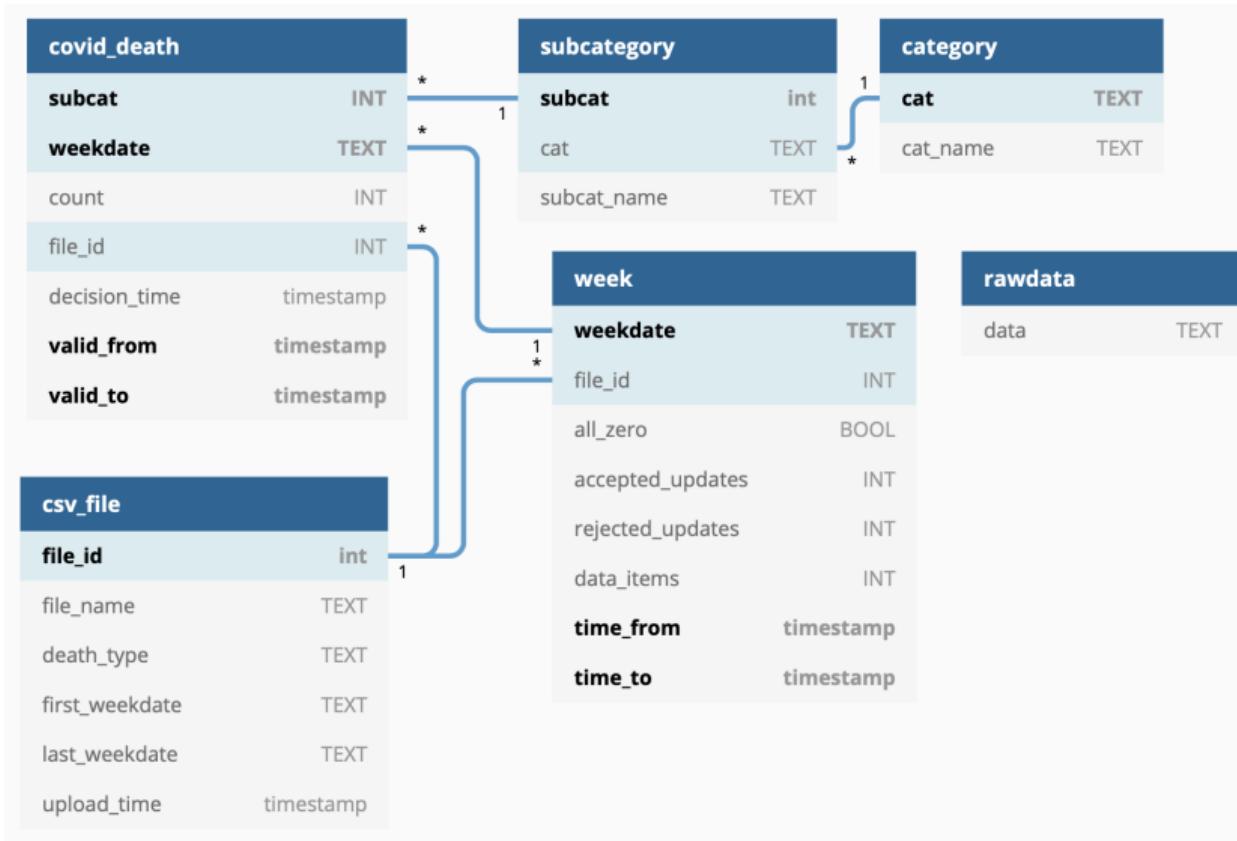
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# Details of Covid case study

# Database schema



# Example queries

```
# Sequenced flat query

var subcat_of_interest = 8;
var week_of_interest = "2020-04-13";

for (y <-> covid_death)
    where
        (vtData(y).subcat==subcat_of_interest
        && vtData(y).weekdate==week_of_interest)

            [(subcat=vtData(y).subcat,
            weekdate=vtData(y).weekdate,
            count=vtData(y).count,
            file_id=vtData(y).file_id,
            valid_from=vtFrom(y),
            valid_to=vtTo(y))
        ]

[(subcat = 8, weekdate = "2020-04-13", count = 80, file_id = 25,
    valid_from = 2021-07-21 11:36:25.955976,
    valid_to = 2021-07-21 12:26:47.082969),
(subcat = 8, weekdate = "2020-04-13", count = 81, file_id = 26,
    valid_from = -infinity,
    valid_to = -infinity),
(subcat = 8, weekdate = "2020-04-13", count = 81, file_id = 27,
    valid_from = 2021-07-21 12:26:47.082969,
    valid_to = infinity),
]
: [(subcat:Int,weekdate:String,count:Int,file_id:Int,
    valid_from:DateTime,
    valid_to:DateTime)]
```

# Example queries

```
# Current time-slice nested query

for (x <-> subcategory)
  where (x.cat=="Sex")

  [(subcat_name=x.subcat_name,
    cat=x.cat,
    results=
      for (y <-> covid_death)
        where (vtData(y).subcat==x.subcat
          && vtTo(y)==forever())
          [(count=vtData(y).count,
            weekdate=vtData(y).weekdate)]
    )
  ]

[(subcat_name = "Female",cat = "Sex",
results = [(count = 5, weekdate = "2020-03-16"), (count = 26, weekdate = "2020-03-23"), (count = 127, weekdate = "2020-03-30"), (count = 262, weekdate = "2020-04-06"), (count = 310, weekdate = "2020-04-13"), (count = 346, weekdate = "2020-04-20"), (count = 279, weekdate = "2020-04-27"), (count = 222, weekdate = "2020-05-04")],
),
(subcat_name = "Male",cat = "Sex",
results = [(count = 5, weekdate = "2020-03-16"), (count = 36, weekdate = "2020-03-23"), (count = 155, weekdate = "2020-03-30"), (count = 348, weekdate = "2020-04-06"), (count = 340, weekdate = "2020-04-13"), (count = 313, weekdate = "2020-04-20"), (count = 247, weekdate = "2020-04-27"), (count = 193, weekdate = "2020-05-04")]
)
: [(subcat_name:String,cat:String,results:[(count:Int,weekdate:String)]),])
```

# Example queries

```
# Sequenced inserts, deletes and updates for valid time

vt_insert covid_death values
  (subcat,weekdate,count,file_id,decision_time)
  [withValidity(
    ( <values to be inserted> ),
    now(),forever())]

for (x <- decs)
  update sequenced (y <-v- covid_death)
  between (now(),forever())
  where (x.weekdate==y.weekdate && x.subcat==y.subcat)
    set (count = x.new_value, file_id=x.file_id)].  

#-----  

update nonsequenced (x <-v- covid_death)
  where (x.cat=="Location")
    set (count = 0).  

# update the count to zero
# for all records with the
# category "Location"

delete sequenced (x <-v- covid_death)
  between (error_from, error_to)
  where (x.cat == "Location").  

# delete records in
# a specific category
# during a given time period

delete nonsequenced (x <-v- covid_death) where (true).  

# delete all records

# these three queries destroy update provenance information!
```