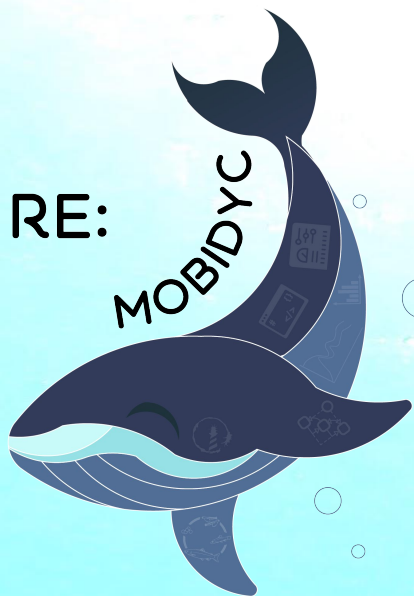




RE:

A Multi-Agent Simulation Platform for Individual-Based Modeling in Biology



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Agenda

- Problem: renovation of a multi-agent simulation platform needed
- Trace-centric architecture
- Implementation on Pharo
- Conclusion

Problem: renovation of IBM platform needed

Mobydic : Individual-Based Modeling platform

pros

- dedicated design for IBM in biology
 - modeling as interaction among **agents** (animats, cells, non-located agents)
 - direct support for **life-history stages** (molting and metamorphosis)
- modeling on GUI that requires **less programming skills**

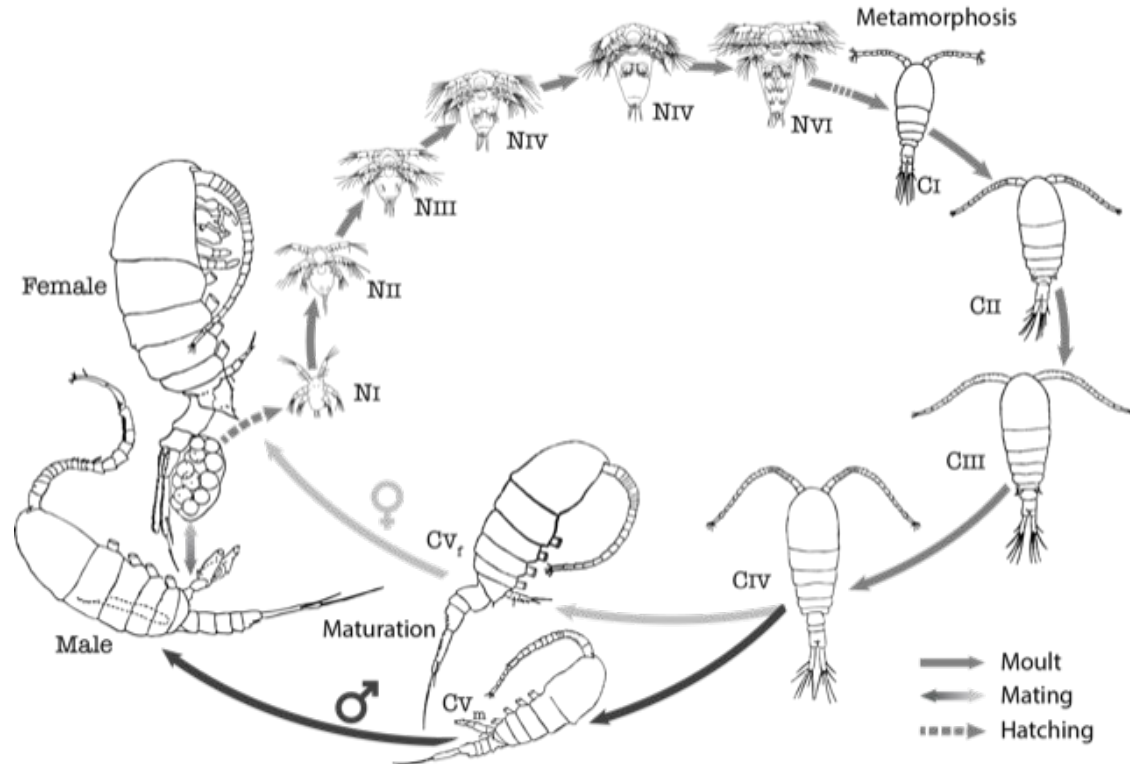
cons

- old code base (on 32bit VisualWorks)
- no maintainers
- doesn't scale

re-design and re-implement based on the same philosophy

➡ re:mobidyc

Example life-history stages (Copepods)



Why Mobidyc failed to scale?

- User-defined agents were responsible for data aggregation and recording.
- History was managed in memory.
- Analysis design was required before running the model.

Resulting in

- Frequent global GC
- Frequent heap expansion
- Repeated executions with minor changes to data aggregation agents

So, we need

- Scalable history management and
- Post hoc analysis: Run first, record everything, then analyze.

Requirements to re:mobidyc

R1 - Support for biology ... especially life-history stages

R2 - Interaction among individuals and environments represented by agents

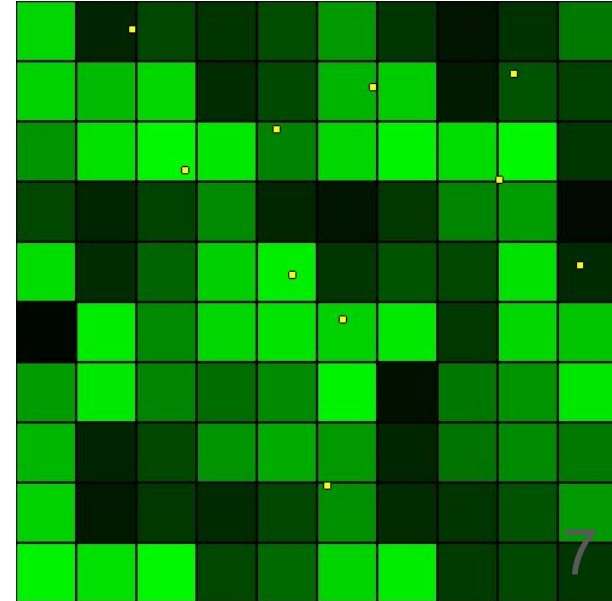
R3 - less imperative programming skills

R4 - Support for variability and post hoc analysis

R5 - Scalability

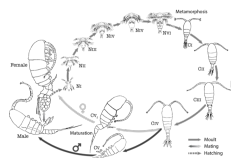
the problem that
Mobidyc suffered from

the user's goal

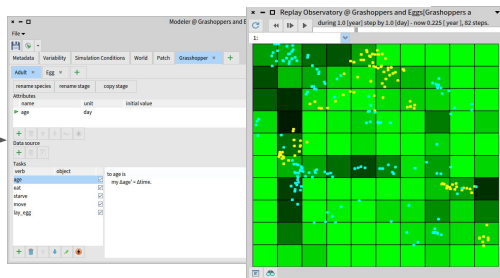


Trace-centric architecture

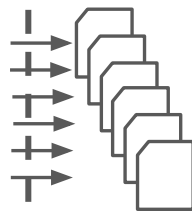
conventional execution-centric approach



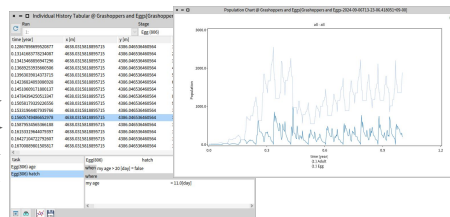
IBM + observer agents



execution engine

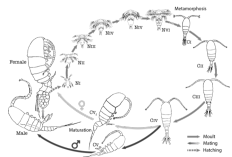


preprocessed
results

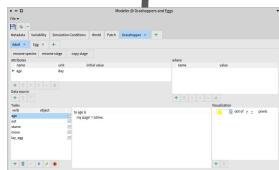


analysis tools

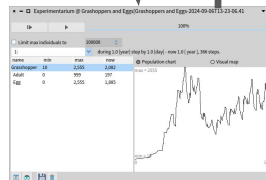
trace-centric architecture



IBM with variability

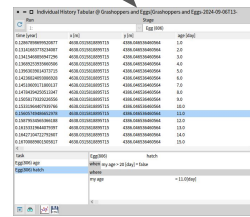
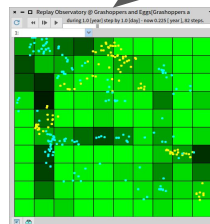


modeling UI

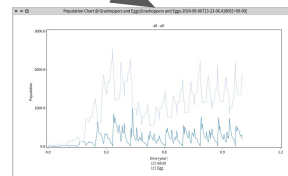


execution engine

execution trace
A complete history = a series of snapshots

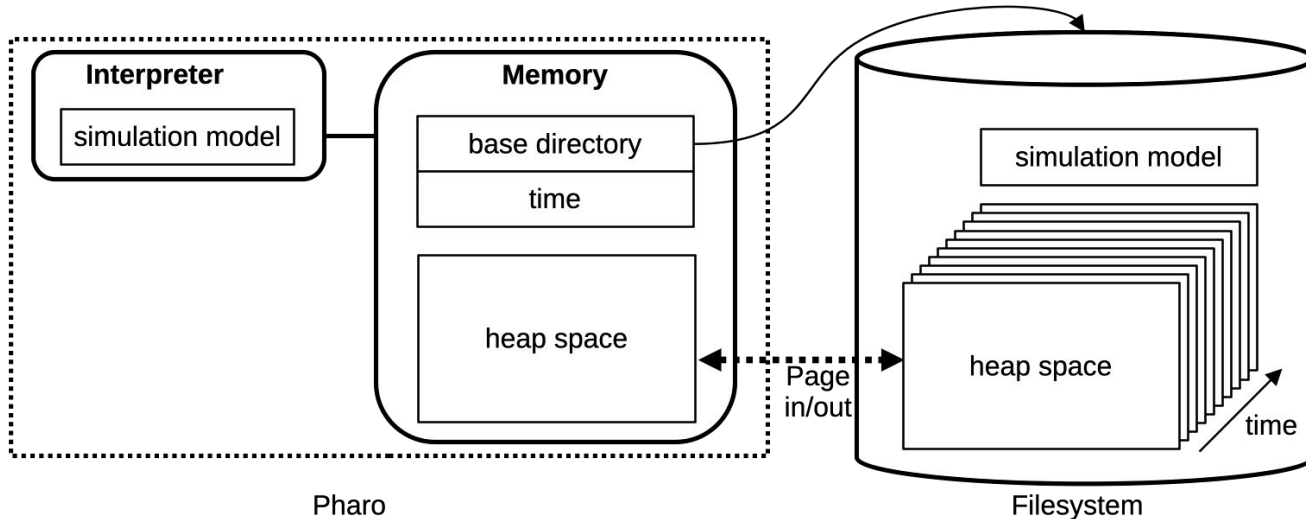


post hoc analysis tools



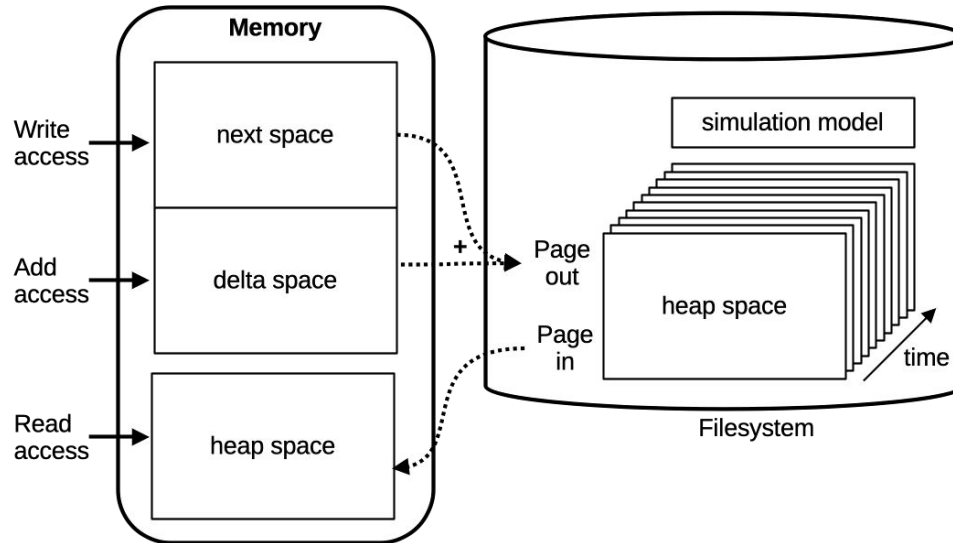
solution to R4/R5: time-indexed virtual memory

- Memory is addressed by (time-step, heap address).
- The entire program state is indexed by time and stored persistently.
- The interpreter accesses only the current time-step “page” during execution.
- The full trace remains available as a time-addressable memory.



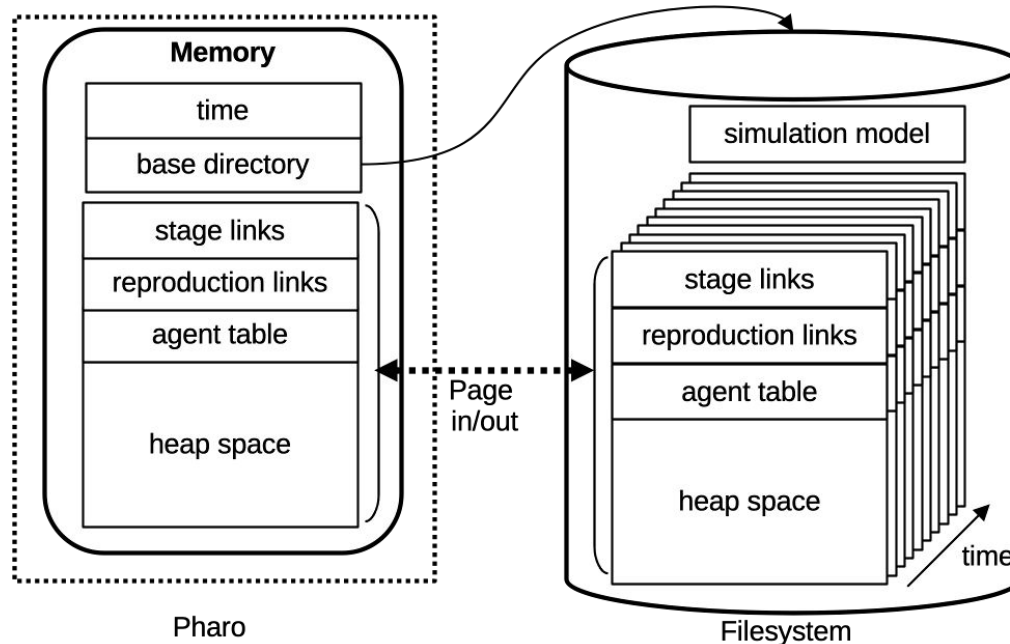
solution to R3: synchronous updating

- Variables are updated through a staged assignment model
 - heap space: current variable values (at:)
 - delta space: incremental variable updates (at:add:)
 - next space: pending variable assignments (at:put:)
- Updates are applied only at transition to the next time step



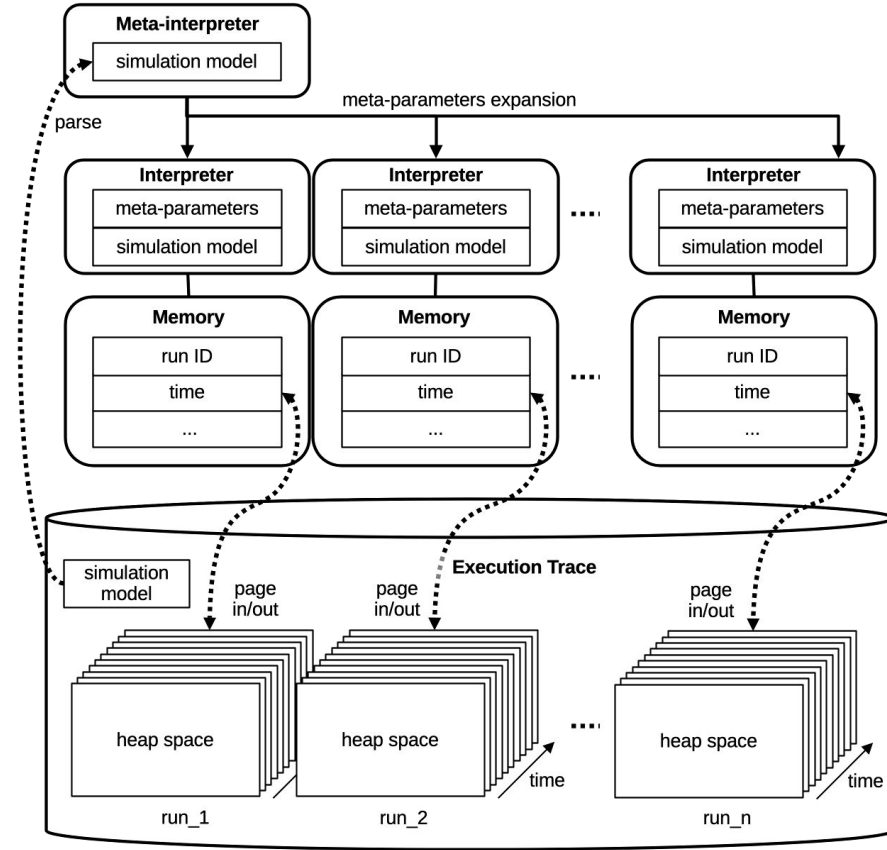
Solution to R1/R2: Domain-aware memory model

- Stage links: encode an individual's life-history progression
- Reproduction links: encode lineage relationships between agents
- Agent table: stage-indexed view of all agents in memory



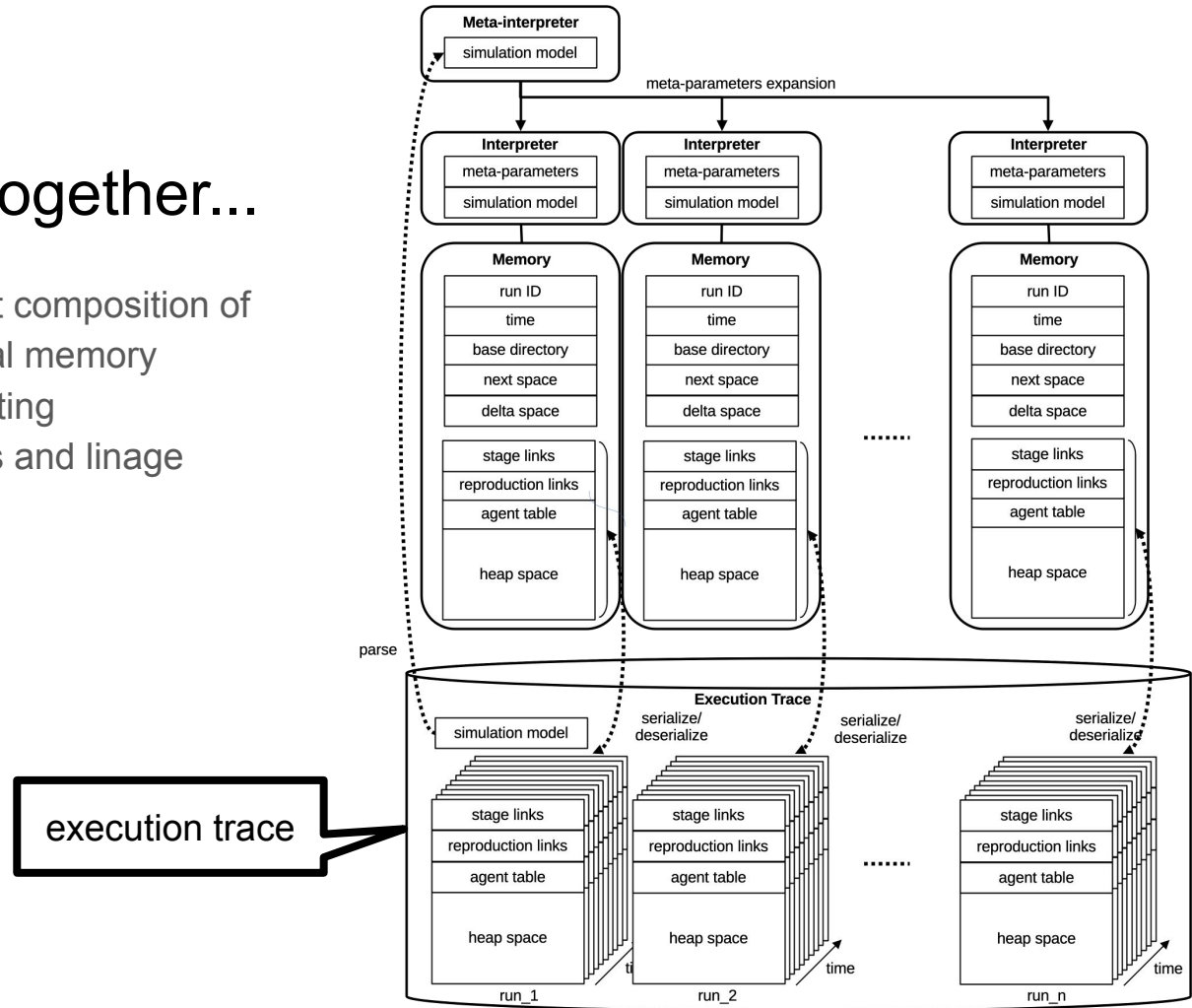
solution to R4: meta-interpreter

- Parameterized simulation models
 - e.g. water temperature = 23, 24, 25 °C
- A meta-interpreter
 - expands meta-parameters into multiple simulation models
 - manages the corresponding interpreters



putting them all together...

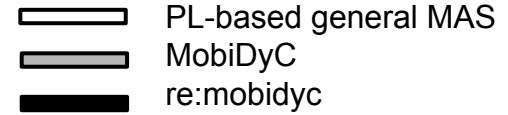
- It looks complex, but just composition of
 - time-indexed virtual memory
 - synchronous updating
 - links for individuals and lineage
 - meta-interpreter



architecture meets requirements

	model	language	(meta-)interpreter	memory	analysis tool
R1 - biology		directives maths	directives maths	links	stages, individuals
R2 - agents modeling		task def	spatial bindings	agent table	
R3 - skills		declarative		synchronous updating	
R4 - variability and analysis			meta-parameter expansion	time-indexed virtual memory	aggregation
R5 - Scalability				time-indexed virtual memory	

Migrations of responsibilities



	model	language	interpreter	memory	post hoc analysis tools
biology-specific concepts	PL-based general MAS	MobiDyC			
		re:mobidyc			
model behavior	PL-based general MAS				
	MobiDyC				
	re:mobidyc				
data consistency	PL-based general MAS				
	MobiDyC				
		re:mobidyc		re:mobidyc	
data aggregation	PL-based general MAS				
	MobiDyC				
					re:mobidyc
data recording	PL-based general MAS				
	MobiDyC				
				re:mobidyc	
variability	PL-based general MAS				
			MobiDyC		
			re:mobidyc		
spatial visualization			PL-based general MAS		
			MobiDyC		
					re:mobidyc

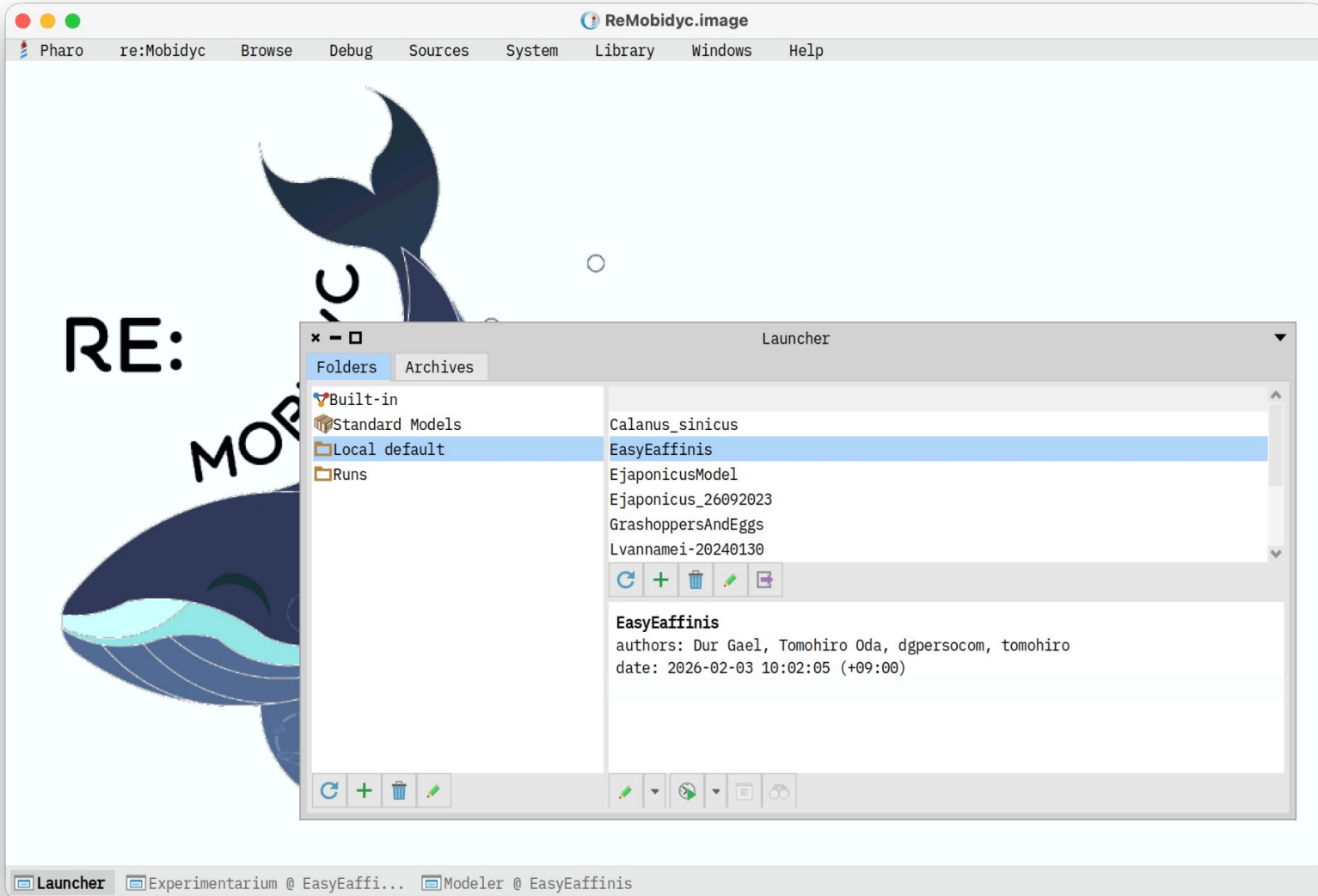
Migration of immersiveness

- Pharo achieves immersiveness through an always-live environment.
- re:mobidyc keeps execution deterministic and static.
- Immersiveness is migrated to post-hoc analysis in re:mobidyc.
- The execution trace (time-indexed virtual memory) becomes the substrate for immersive post-hoc interaction.

Implementation on Pharo

Why Pharo?

- Well-maintained modern Smalltalk implementation/dialect.
 - 64bit VM/Image, multiple platform
 - SmallInteger and SmallFloat64 are immediate objects
 - active and supportive community
- Excellent environment for DSL development
 - experience of ViennaTalk
 - PetitParser
- flexible UI frameworks
 - Flexibility and customizability of Spec2
 - Visualization by Roassal3



ReMobidyc.image

Pharo re:Mobidyc Browse Debug Sources System Library Windows Help

Modeler @ EasyEaffinis

File

Metadata Variability Simulation Conditions World Patch Eaffinis +

Copepodite3 x Copepodite4f x Copepodite4m x Copepodite5f x Copepodite5m x AdultFemale x AdultMale x +

rename species reorder species rename stage reorder stages copy stage

Attributes

name	unit	initial value
degreeday	° C day	0 [° C day]
maxDD	° C day	world's temperature*longevity
rddLT	° C day	world's temperature*latencyTime
ddLT	° C day	0 [° C day]

Data source

Tasks

verb	object
cumulDD	☒
die_by_age	☒
move	☒
cumulDDL	☒
cumulDDEDT	☒
spawn	☒
survive	☒
reproduce	☒

to spawn is

when my ddLT >= my rddLT and my ovigerous = 0

my ovigerous' = 1

my rddEDT' = world's temperature*embryonicDevTime

my ddLT' = 0.0 [° C day]

my clutchsize' = gamma 14.15 scale 0.07373*mCS

my ddEDT' = 0.0 [° C day]

where

embryonicDevTime = (gamma 59.27 scale 0.01693*mEDT)[day]

mEDT = 36.8*power((° C)(world's temperature-0 [° C]), -1.04)

mCS = 43.64*power((° C)(world's temperature)/(° C)17.73

[° C]*power(qiCS, uCS), 0.9704)

qiCS = (° C)(24 [° C]-world's temperature)/(° C)(24 [° C]-17.73 [° C])

uCS = (° C)(24 [° C]-17.73 [° C])/(° C)(17.73 [° C]-

where

name	value
longevity	(gamma 14.58 scale 0.0713*mLifeSpan
mLifeSpan	633.7*power((° C)(world's temperatu
latencyTime	(gamma 2.468 scale 0.4105*mLT)[day]
mLT	82.31*power((° C)(world's temperatu

Visualization

NOvAdultFemaleCalanoid.png 0.03

Launcher Experimentarium @ EasyEaffi... Modeler @ EasyEaffinis

RE:

MOBIDYC

Pharo

re:Mobidyc

Browse

Debug

Sources

System

Library

Windows

Help

ReMobidyc.image

Experimentarium @ EasyEaffinis[EasyEaffinis-2026-07-07T11-03-46.70159+03-00]

70%

Limit max individuals to

100000

1:t_delta_ad=260 [day]

▼

during 100.0 [day] step by 6.0 [h] - now 70.8 [day], 283 steps.

name	min	max	now
Eaffinis	35	2,319	1,905
Nauplii1to0		1,427	1,014
Nauplii4to0		553	4
Copepodite0		353	6
Copepodite0		346	11
Copepodite0		323	24
Copepodite0		194	20
Copepodite0		219	10
Copepodite0		236	42
Copepodite0		231	65
AdultFemal5		304	304
AdultMale 0		405	405

● Population chart

○ Visual map

max = 2319

min = 35

0

70.8

📄

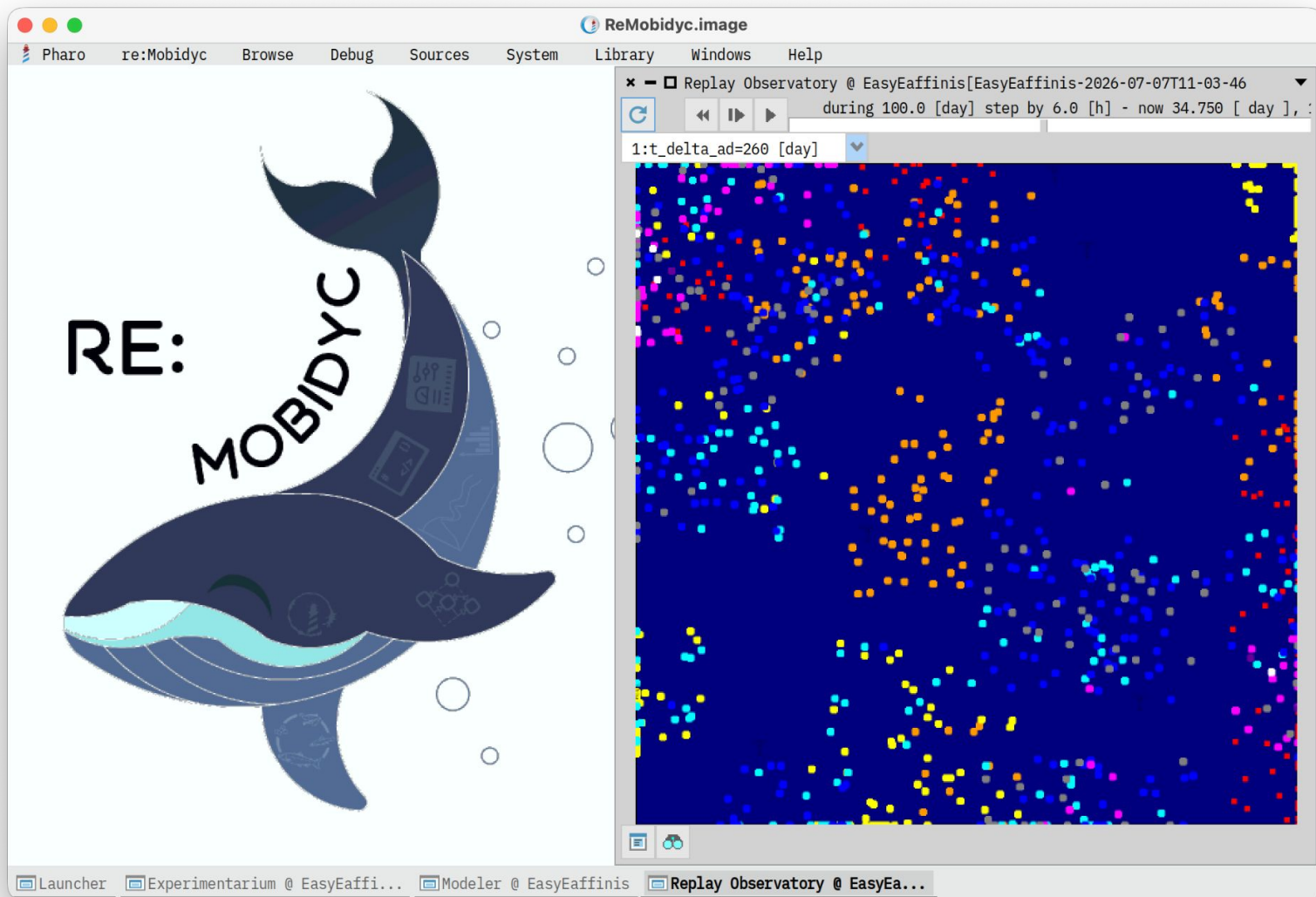
🔍

💾

🗑️

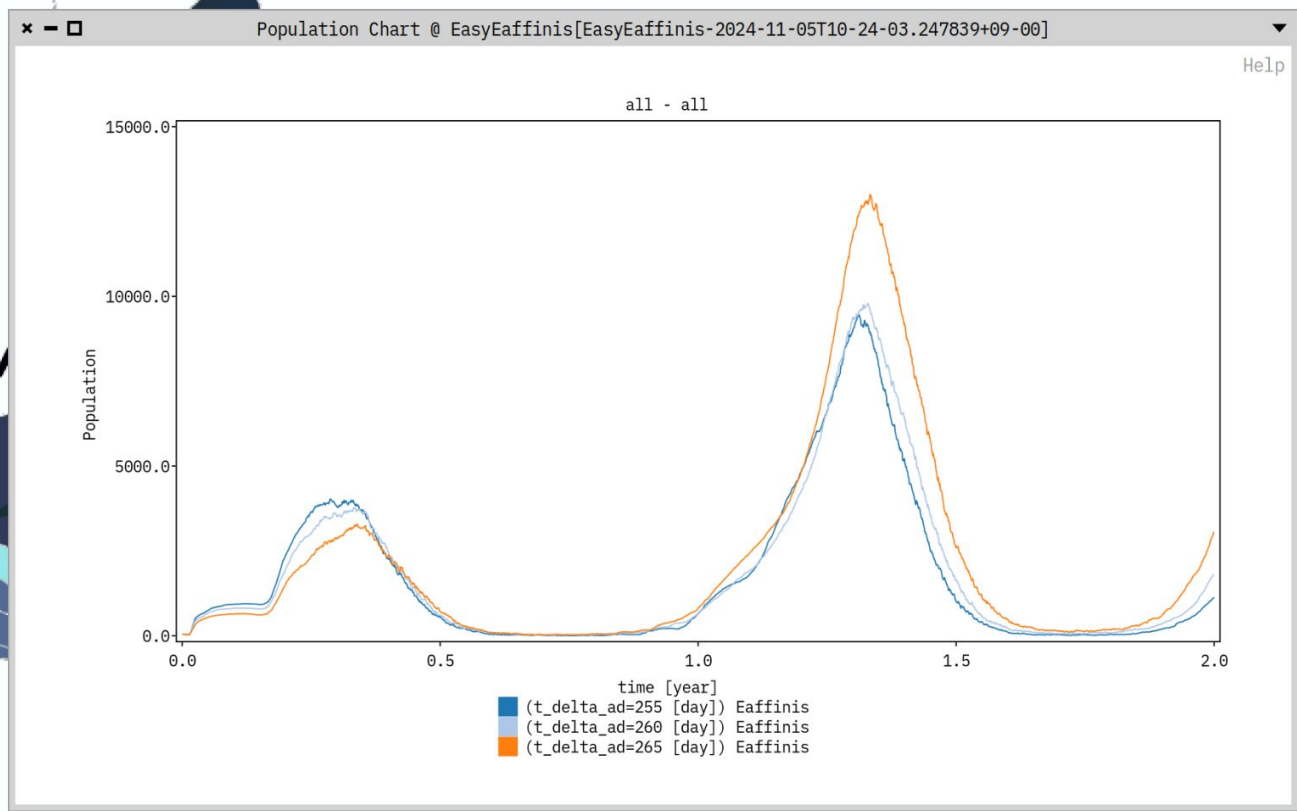
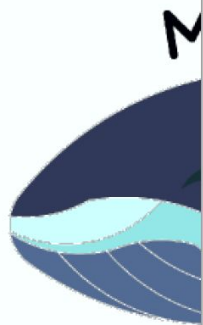
Launcher

Experimentarium @ EasyEaffi...





RE:



ReMobidyc.image

Pharo re:Mobidyc Browse Debug Sources System Library Windows Help

Snapshot Tabular @ EasyEaffinis[EasyEaffinis-2024-11-05T10-24-03.247839+09-00]

Run Agent

1:t_delta_ad=255 [day] Eaffinis(AdultFemale)

Time	ID	x [m]	y [m]	degreeday [° C day]	maxDD [° C day]	rddLT [°
1.1225 [year]	517045	0.5027903660974943	0.24806127174129164	448.6644613970437	646.8291866983091	81.989971
1.1232 [year]	517881	0.6285114339108138	0.8530072050262526	433.28372833987146	578.1245221964698	37.557812
1.1239 [year]	522394	0.7367168373203334	0.30535733113367247	388.8589369658147	698.3749120997282	60.925654
1.1246 [year]	541799	0.0	0.48164688795355015	288.53840618083325	691.9693371799835	78.212492
1.1253 [year]	542763	0.07296265807518673	0.6299110043192526	284.4168163936158	708.2536838969769	90.411976
1.1259 [year]	569299	0.5674858448634787	0.31199214816988335	211.08142975531644	475.0897130263527	69.239744
1.1266 [year]	583162	0.8013976178939466	0.7148103000873351	181.10952511969649	833.4255196652659	78.796794
1.1273 [year]	587494	1.0	0.862580121859146	172.5982323718833	780.4112407708487	39.214943
1.1280 [year]	588249	0.6179745398244986	0.23928364212087117	170.91189632799188	946.0108414676112	100.17946
1.1287 [year]	589042	0.1012207325060672	0.8715864402078342	169.23079964622247	820.0367098381943	95.074631
1.1294 [year]	589053	0.5495981023459062	0.1424116982560222	169.23079964622247	316.7227831499749	46.669983
1.1300 [year]	590769	0.09784511778971866	1.0	165.88420668266176	376.40917377921994	90.487832
1.1307 [year]						
1.1314 [year]						
1.1321 [year]						
1.1328 [year]						
1.1335 [year]						
1.1342 [year]						
1.1348 [year]						
1.1355 [year]						
1.1362 [year]						
1.1369 [year]						
1.1376 [year]						
1.1383 [year]						
1.1389 [year]						

task AdultFemale(588249) move

AdultFemale(588249) cumuIDD

AdultFemale(588249) die_by_age

AdultFemale(588249) move

AdultFemale(588249) cumuDDLT

AdultFemale(588249) cumuDD EDT

AdultFemale(588249) spawn

AdultFemale(588249) survive

AdultFemale(588249) reproduce

my d/dt x' = cos(theta)*r = 9.64071453355697e-6[m/s]

my d/dt y' = sin(theta)*r = -2.6564305529155867e-6[m/s]

where

r = 0.01[mm/s]

theta = 344.59483325909343[degree]

Launcher Population Tabular @ E... Population Chart @ Eas... Snapshot Tabular @ Eas... Individual History Tab...

ReMobidyc.image

Pharo re:Mobidyc Browse Debug Sources System Library Windows Help

Individual History Tabular @ EasyEaffinis[EasyEaffinis-2024-11-05T10-24-03.247839+09-00]

Run Stage

1:t_delta_ad=255 [day] AdultFemale (3505484)

time [year]	x [m]	y [m]	degreeday [°]	Nauplii1to3 (3495719)	Nauplii4to6 (3498103)	Copepodite1 (3500296)	Copepodite2 (3501436)	Copepodite3 (3502187)	Copepodite4f (3502976)	Copepodite5f (3504053)	AdultFemale (3505484)
1.6283367556468173	0.1466395525359821	0.747017101895409	78.599496992								
1.6290212183436004	0.24649364211131794	0.9385508085767157	83.850450049								
1.6297056810403834	0.3776559036376676	1.0	89.102569217								
1.6303901437371664	0.5729208076046118	1.0	94.355817822								
1.6310746064339494	0.7169694923438372	1.0	99.610159171								
1.6317590691307324	0.6011904732925863	1.0	104.86555655								
1.6324435318275154	0.8077709239303504	1.0	110.12197322								
1.6331279945242985	0.6454104310999982	0.8575392321799256	115.37937245095343	531.8677049633153	27.585667737731097	0.0					
1.6338124572210815	0.5870854400408503	1.0	120.63771744748959	531.8677049633153	27.585667737731097	5.258344996536167					
1.6344969199178645	0.5291693184889161	0.7919093397954113	125.89697143070072	531.8677049633153	27.585667737731097	10.517598979747302					

task AdultFemale(3505484) survive

AdultFemale(3505484) cumulDD when uniform 0 to 1 > power((1/day)(85-30*2*cos(2*3.14 [rad]/365 [day]*(time-255 [day])))[%/day], (day)(Δtime)) = true

AdultFemale(3505484) die_by_age with die

AdultFemale(3505484) move where

AdultFemale(3505484) cumulDDLT time = 1.6344969199178645[year]

AdultFemale(3505484) cumulDDEDT Δ time = 6.0[h]

AdultFemale(3505484) spawn

AdultFemale(3505484) survive

AdultFemale(3505484) reproduce

Launcher Population Tabular @ E... Population Chart @ Eas... Snapshot Tabular @ Eas... Individual History Tab...

packages

Application/UI

239 classes

2186 methods

ReMobidyc-Visualization

18 classes / 170 methods

ReMobidyc-Diagrams

6 classes / 33 methods

ReMobidyc-Spec2

131 classes / 1728 methods

ReMobidyc-Repository

8 classes / 206 methods

ReMobidyc-Chronicle

2 classes / 49 methods

Engines

90 classes

1118 methods

ReMobidyc-Interpreter

63 classes / 775 methods

ReMobidyc-Storage

6 classes / 227 methods

ReMobidyc-DataSource

21 classes / 116 methods

Languages /

Runtimes

125 classes

1662 methods

ReMobidyc-Language

115 classes / 1551 methods

ReMobidyc-Units

8 classes / 101 methods

ReMobidyc-Application

2 classes / 10 methods

It scaled!

- 874,705 individuals (at the peak step)
- 8,766 simulation steps (6 years by 6 hours)
- 91 GB trace
- 968 MB memory (MEM of the pharo process)

91 GB trace managed with less than 1 GB of memory

Lessons from implementation and use in action

- Modeling Language

- Declarative modeling has a learning curve.
 - Tutorials are essential.

- Interpreter

- Creating contexts with spatial bindings dominates execution costs
 - needs further optimization.
- (Meta-)interpreters are also useful in analysis tools.

- Memory

- Time-indexed virtual memory achieved scalability.
- File I/O became significant ... further improvements are needed.

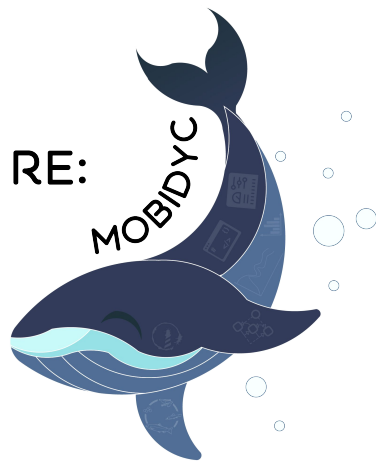
- Analysis

- Post hoc analysis worked well so far.
- More immersive analysis tools remain to be designed.
- Users still expect immediate visual feedback during execution.

conclusion

Takeaways

- The trace-centric architecture changed the allocation of responsibilities. Time-indexed virtual memory improves verifiability for scientific computing.
- Immersiveness also shifted from execution time to post-hoc analysis. The execution trace is an immersive environment.
- Pharo is an excellent platform for building such an "extreme" DSL.
- re:mobidyc is now being used for biological simulations studies.
 - **Okura et al. (2025)**
"First individual-based model to study the impact of temperature on Sakura shrimp larvae development: Integrating experimental insights",
Aquaculture, vol. 595.
 - **Takahashi et al. (2024)**
"Elucidating the Disrupted Seasonal Cycle of Eodiaptomus japonicus (Calanoida, Copepoda) in Lake Biwa: Insights from an Individual-Based Model",
Diversity, 16 (6).



The development of re:mobidyc is partially supported by JSPS KAKENHI Grant Number 24K09052.

Resources

- GitHub: <https://github.com/ReMobidyc/ReMobidyc/>
- Binary packages: <https://viennatalk.org/builds/remobidyc/latest/>
- Microsoft Store: search "re:mobidyc"