# Individual-based Modeling for Salmonid Management

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http://math.humboldt.edu/~ecomodel/

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## Credits

- Research collaborators:
  - Steve Railsback, Lang, Railsback, and Associates
  - Bret Harvey, USFS Redwood Sciences Lab
  - Software: Steve Jackson, Jackson Scientific Computing

Funding: EPA STAR Grant

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## Presentation Objectives

- inSTREAM our individual-based trout model
- Advantages of IBMs for modeling fish population response to stressors
- Example applications of our stream trout IBM to management research and decision-making

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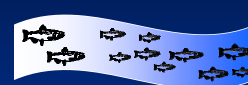
## What is an IBM?



- A model of the environment

  +
- Models of individual animals
  - The mechanisms by which the environment affects an individual
  - The mechanisms by which individuals interact
  - The behaviors individuals use to adapt to their environment and each other
- Population responses that emerge from individual behaviors

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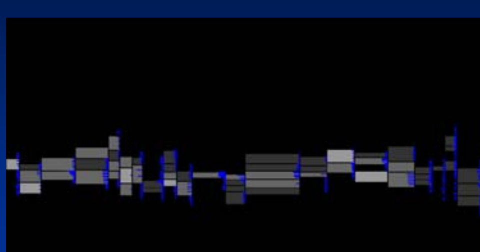
## What is an IBM? Demo



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## Why an Individual-based Model?

- IBM's resolve the two fundamental dilemmas of modeling:
  - Models usually assume many individual organisms can be described by a single variable like population size or biomass. IBM's provide for individuals and their differences.
  - Most models don't distinguish between organisms' locations. IBM's provide for distinctive interactions with neighboring individuals and the local environment.

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## Advantages of IBMs for Modeling Fish Population Response to Stressors

- Complex, cumulative effects can be simulated:
  - Base flow
  - High and low flows: timing and magnitude
  - Temperature
  - Turbidity
  - Losses of individuals (angler harvest, diversion entrainment)
  - Food production
  - Reproduction, recruitment
  - Species interactions: competition, predation
  - ...

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## Advantages of IBMs for Modeling Response to Stressors

- Complex, cumulative effects can be simulated:
- These complex interactions *emerge* from individual-level mechanisms
  - instead of having to be foreseen and built into a model
  - you just have to model how stressors affect *individuals*

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## Advantages of IBMs

- IBMs are testable in many ways
  - They can produce many kinds of predictions that can be tested with many kinds of data
    - Habitat selection patterns over space, time, flow ...
    - Statistical properties of population (size, abundance)
    - Trends in abundance with environmental factors
    - etc.

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## Advantages of IBMs

- IBMs provide a way out of the complexity - uncertainty dilemma:
  - A well-designed IBM is a collection of *simple* submodels for separate processes at the individual level
  - Each submodel can be parameterized and tested with all the information available for its process
  - Yet IBMs can simulate complex population level responses

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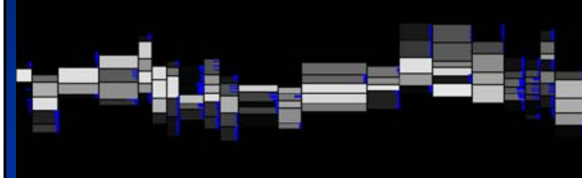
## Stream Trout Model

- Habitat is modeled as rectangular cells
- External hydraulic model simulates how depth, velocity vary with flow

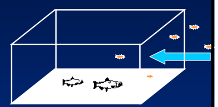


## Stream Trout Model

- Habitat:
  - Water depths and velocities
  - Temperature, turbidity
  - Food availability
  - Daily time step
- Fish:
  - Habitat selection (choosing the best cell)
  - Feeding and growth
  - Mortality
  - Spawning & incubation

## Feeding Model

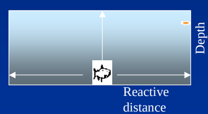
- Drift feeding strategy



  – Food intake per fish:

    *Food concentration × velocity × capture area.*

*Capture area:*

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## Feeding Model

- Food intake varies between drift and search feeding strategies
  – Relative advantages depend on flow, fish size, habitat
- Food intake can be limited by competition (food consumed by bigger fish)
- Each fish picks the feeding strategy offering highest growth
  – Preferred strategy can vary among cells

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## Growth Model (bioenergetics)

- Growth = Food intake - metabolic costs
  – Metabolic costs:
    - increase with swimming speed
    - increase with temperature

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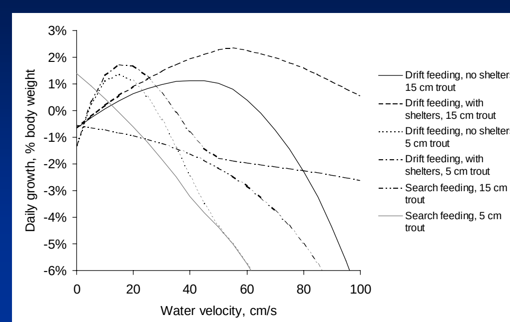
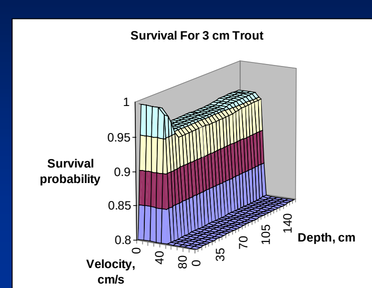
## Foraging Model: Growth vs. Velocity, Fish Size, Feeding Strategy




## Survival Model

- Survival probabilities:
  – Vary with habitat
  – Depend on fish size, condition
  – Include:
    - Poor condition (starvation)
    - Terrestrial predation
    - Aquatic predation
    - High temperature
    - High velocity (exhaustion)
    - Stranding (low depth)

## Survival Model: Overall Risks

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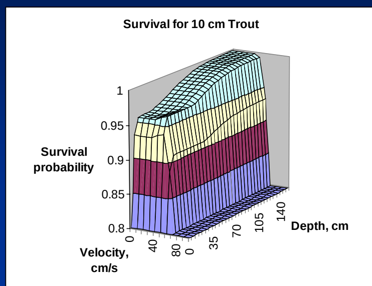
## Survival Model: Overall Risks

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## Habitat Selection: Overview

- Habitat selection is critical:
  - Moving is the primary way fish adapt to changing conditions
- Our approach assumes fish use behaviors that evolved to maximize fitness

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## Habitat Selection Rules

- Move to the cell that offers highest potential "fitness"
  - (within the radius that fish are assumed to be familiar with)
  - Railsback, S. F., R. H. Lamberson, B. C. Harvey and W. E. Duffy (1999). Movement rules for spatially explicit individual-based models of stream fish. *Ecological Modelling* **123**: 73-89.

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## Habitat Selection: Fitness Measure

- Fish move to cell offering highest fitness
- Key elements of fitness are:
  - Future survival
  - Attaining reproductive size

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## Habitat Selection: Summary
### *How a Fish Rates A Potential Destination Cell*

- Considers:
  - Potential growth in cell (function of habitat, competition)
  - Mortality risks in cell (function of habitat)
  - Its own size and condition
- Probability of surviving for 90 days in the cell?
  - Assuming today's conditions persist for the 90 days
- How close to reproductive size after 90 d in the cell?
- Rating = Survival probability × fraction of reproductive size

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## Habitat Selection

- Many realistic behaviors emerge:
  - Normal conditions: territory-like spacing
  - Short-term risk: fish ignore food and avoid the risk
  - Hungry fish take more chances to get food (and often get eaten)
  - Conditions like temperature, food availability, fish density affect habitat choice

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## Analyzing Individual-based Models

- The "pattern-oriented" analysis approach:
  - Test specific processes of an IBM by whether it reproduces a wide range of behaviors that emerge from the process
  - Test a complete IBM by whether it reproduces a wide range of observed population-level patterns
  - Railsback, S. F. (2001). Getting "results": the pattern-oriented approach to analyzing natural systems with individual-based models. *Natural Resource Modeling* **14**: 465-474.

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## Pattern-Oriented Analysis of inStream

- Validation:
  - Individual level
    - Railsback, S. F. and B. C. Harvey (2002). Analysis of habitat selection rules using an individual-based model. *Ecology* **83**: 1817-1830.
  - Population level
    - Railsback, S. F., B. C. Harvey, R. H. Lamberson, D. E. Lee, N. J. Claasen and S. Yoshihara (2002). Population-level analysis and validation of an individual-based cutthroat trout model. *Natural Resource Modeling* **15**: 83-110.

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## Validation of Habitat Selection Rules: Six Patterns (a)

- Feeding hierarchies
- Movement to channel margin during high flow
- Juveniles respond to competing species by using less optimal habitat (higher velocities)

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## Validation of Habitat Selection Rules: Six Patterns (b)

- Juveniles respond to predatory fish by using shallower, faster habitat
- Use of higher velocities in warmer seasons
- Habitat shift in response to reduced food

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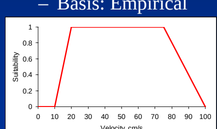
## Expected Reproductive Maturity vs. Habitat Suitability Criteria as Indicators of Habitat Quality

- PHABSIM habitat suitability criteria (HSC)
  - Basis: Empirical




- Expected Reproductive Maturity (EM)
  - Basis: Mechanistic models of feeding, mortality risks, fitness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## EM vs. HSC Indicators of Habitat Quality

- HSC

  Habitat rating varies only with fish life stage:

  *fry, juvenile, adult, spawning*

  *(occasionally: season)*

- EM

  Habitat rating varies with:
  - ↗ Fish size
  - ↗ Fish condition
  - ↗ Temperature & season
  - ↗ Food availability
  - ↗ Cover for hiding, feeding
  - ↗ Other factors affecting growth or survival

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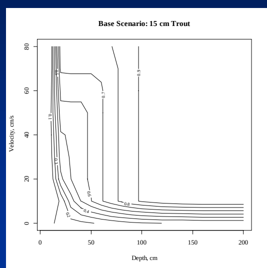
## EM as an Indicator of Habitat Quality




- Adult trout
  - drift feeding
  - using velocity shelter

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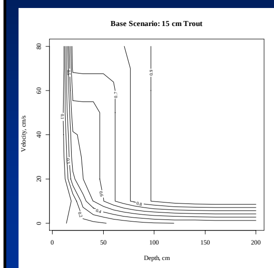
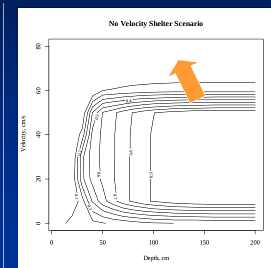
## EM as an Indicator of Habitat Quality: With vs. Without Velocity Shelters for Drift Feeding

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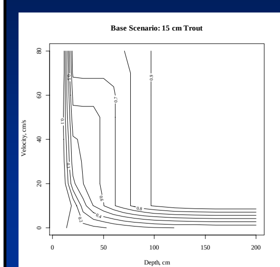
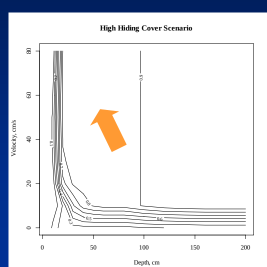
## EM as an Indicator of Habitat Quality: Without vs. With Hiding Cover

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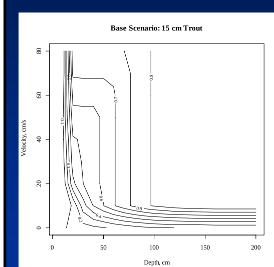
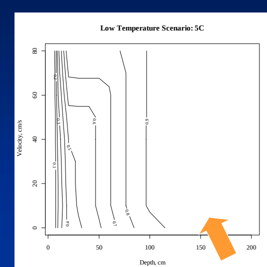
## EM as an Indicator of Habitat Quality: 15° vs. 5° Temperature

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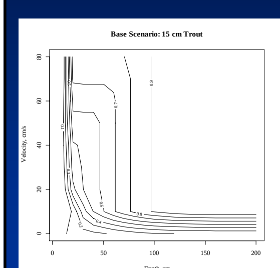
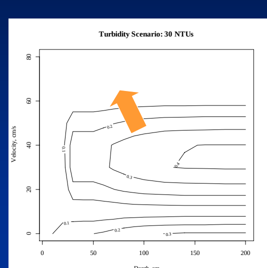
## EM as an Indicator of Habitat Quality: Low vs. High Turbidity

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## Example Use of IBM for Management Research: Effect of Habitat Complexity on Population Dynamics

- Observed pattern: When deep pools are eliminated, a lower abundance of large trout results:
  - Bisson & Sedell (1984) observed fewer pools & fewer large trout in clearcuts
- Simulation experiment:
  - Simulate populations over 5 years with, without pool habitat in the model
  - Railsback, S. F., B. C. Harvey, R. H. Lamberson, D. E. Lee, N. J. Claasen and S. Yoshihara (2002). Population-level analysis and validation of an individual-based cutthroat trout model. *Natural Resource Modeling* **15**: 83-110.

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## Effect of Habitat Complexity on Population Dynamics

- Simulation results (1):
  - Abundance of all age classes was lower when pools were removed
  - Impact was greatest on oldest age class
  - Terrestrial predation caused the lower abundance - pools provide shelter from terrestrial predators

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## Effect of Habitat Complexity on Population Dynamics

- Simulation results (2):
  - Size of age 0 and 1 trout *increased* when pools were removed -
  - Why??

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## Effect of Habitat Complexity on Population Dynamics

- Simulation results (2):
  - Size of age 0 and 1 trout *increased* when pools were removed -
    - Abundance decreased, so there was less competition for food
    - Age 1 trout were forced to use faster, shallower habitat where predation risk is higher
      BUT food intake and growth is higher

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## Example IBM Application: Effects of Instream Flow Magnitude & Variability

- How does the amount *and timing* of flow affect trout *abundance* and *growth*?
- Site: Little Jones Creek
  (3rd order coastal stream in N. California)
- Scenarios: hypothetical hydropower reservoir
  - Constant flow *vs.* Natural monthly mean flow
- Simulations: 10 years, 5 replicates per scenario

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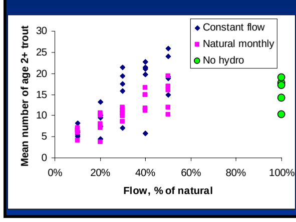
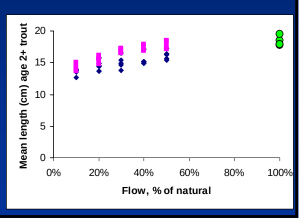
## Example IBM Application: Effects of Instream Flow Magnitude & Variability

- How does the amount *and timing* of flow affect trout *abundance* and *growth*?




## Example Application: Effects of Turbidity

- Turbidity decreases feeding ability, but decreases predation risk
  *What are the population-level consequences?*
- Site: Little Jones Creek
- Five turbidity scenarios:
  - Turbidity = *x* Q
  - Five values of *x*: very clear to very turbid streams

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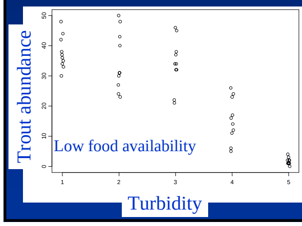
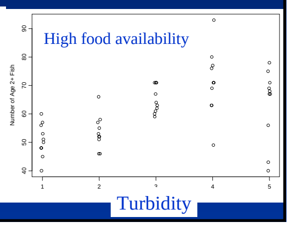
## Example Application: Effects of Turbidity

- Result: Interactions between turbidity and food availability are strong




## Example Use of IBM for Management Research: Habitat Selection vs. Habitat Quality

- Theory to be tested: The habitat that animals use most often is the best habitat
  - This assumption is the basis for many management models
  - It is widely questioned but very difficult to test in the field
- "Relations between habitat quality and habitat selection in a virtual trout population." Railsback, S. F., H. B. Stauffer, and B. C. Harvey. (to appear in *Ecological Applications*.)

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## Habitat Selection vs. Habitat Quality

- "Habitat Selection" = the <u>observed</u> choice of habitat
- DEN is evaluated as observed animal density

DEN= (# animals using a habitat type) / (area of habitat type)

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## Habitat Selection vs. Habitat Quality

- "Habitat Quality" or Fitness Potential (FP) = the fitness provided to an animal by a habitat type, in the absence of competition
  - "Preference": the habitat a fish selects in absence of competitors
- In our IBM:
  - We know the FP of each habitat cell because we programmed it
  - FP varies among habitat cells with water depth, velocity, feeding shelter, hiding shelter

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## Habitat Selection vs. Habitat Quality

- The experiment:
  - Observe DEN (fish density) in each habitat cell (snapshot)
  - Calculate FP for each cell
  - Examine: How well does DEN predict FP? (What can you learn about the quality of habitat by observing the habitat that animals use?)
  - Three ages of trout examined separately

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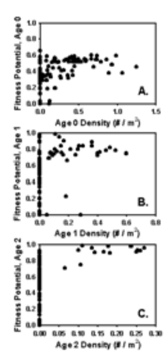
## What Does Habitat Selection Tell You about Habitat Quality?? *Not much!*

- Cells with high density usually are fairly high quality
- Many high quality cells have zero fish
- There is no predictive relationship between observed fish density and habitat quality



## Management Research with the IBM: *Why is There So Little Relation Between Habitat Selection and Habitat Quality?*

- (1) Competition:
  - Smaller trout don’t use the habitat that is best for them because they are excluded by larger fish

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## Why is There So Little Relation Between Habitat Selection and Habitat Quality?

- (2) Unused and unknown habitat:
  - Good habitat for large trout may be vacant because there are not enough trout to use it all
  - Trout may not use the best available habitat because it is too far away to know about

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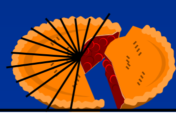
## Why is There So Little Relation Between Habitat Selection and Habitat Quality?

- (3) Cells where food is plentiful but hard to catch can support more fish at lower fitness:
  - Example: Cells with high velocity
  - Each fish can catch less food than optimal
  - Because each fish gets less of the food, more fish can share the cell



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## Why is There So Little Relation Between Habitat Selection and Habitat Quality?

- (4) Cells where food is plentiful but mortality risks are high can support more fish at lower fitness:
  - Density is high because there is plenty of food *but*
  - Fitness is low because mortality risk are high

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## Habitat Selection vs. Habitat Quality

- Conclusions:
  - Observed patterns of habitat selection by animals tell us little about how good the habitat is
  - But does this mean models based on habitat selection are worthless??

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## Are There Problems with Models Based on Habitat Selection?

- A second simulation experiment:
  - A *good* habitat selection model can be a useful predictor of population response over short times
    - *When* habitat modifications are small
    - *And* it is a dominant species or life stage
  - BUT:
    - Habitat selection models have fundamental problems (mainly: neglecting that habitat selection varies over time)

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## Conclusions: Key advantages of IBMs for assessing impacts of multiple stressors on fish

- IBMs can be used to address more questions that are difficult to address with other modeling approaches
- IBMs can be more credible than alternatives
  - More testable
  - Able to simulate complex responses to many stressors without high parameter uncertainty

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## Conclusions: Potential Limitations of IBMs

- Computation: There is a limit to how many fish / how much habitat we can simulate (overcome with bigger computers, clusters?)
- Models for new groups of fish can be expensive to build
- Expertise: Few biologists are familiar with IBMs (or the mechanistic, individual-based view of ecology)
- Acceptance by managers: IBMs are unfamiliar, not as simplistic as alternative approaches
- We haven't done anadromy yet (but have put a lot of work into concepts and software)

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## Conclusions: Our Status

- Continued evolution, application of the trout model
  - Diel shifts in habitat & activity: feeding vs. hiding
  - Sub-daily time steps and fluctuating flows
- Interest in new applications of our salmonid IBMs
  - Instream flow assessment
  - Assessment of restoration activities ...
  - Regional stressor-response applications
- Development of new models (juvenile Colorado pikeminnow)
- Development & publication of theory & software

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## Individual-based Modeling for Salmonid Management

Humboldt State University Humboldt Mathematics

http://math.humboldt.edu/~ecomodel/

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