

Implementation of analogue arithmetic circuitry in plants

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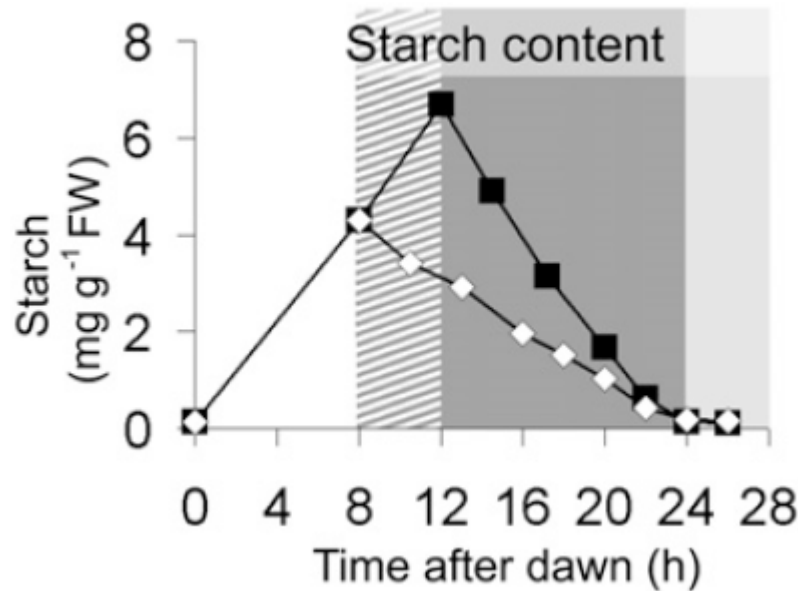
Starch degradation in *Arabidopsis*

- During the night plants degrade starch made by photosynthesis during daylight
- Accumulation and degradation both linear

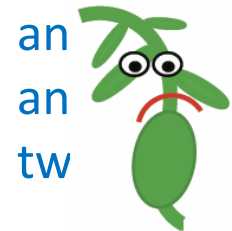
- Degradation rate too high: if night comes early?



- Starch content is only readjusted!



- Degradation rate too low: slower growth



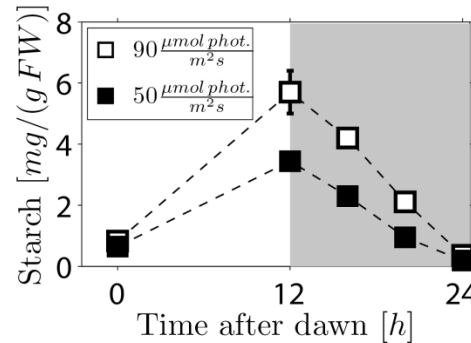
- Starch content is only readjusted!

Graf et al, PNAS (2010)
Lu et al Plant Phys. (2005)

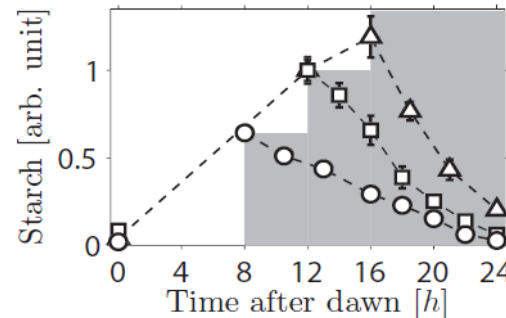
Computation of degradation rate is robust

Correct degradation rate is computed ...

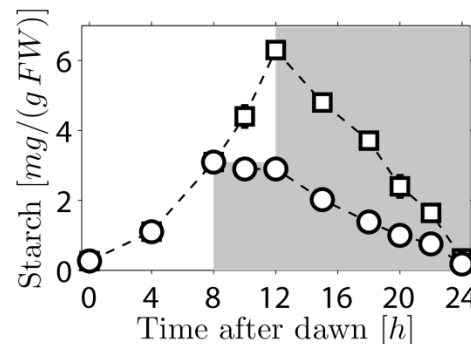
• When light intensity is varied



• When subject to early or late onset of night



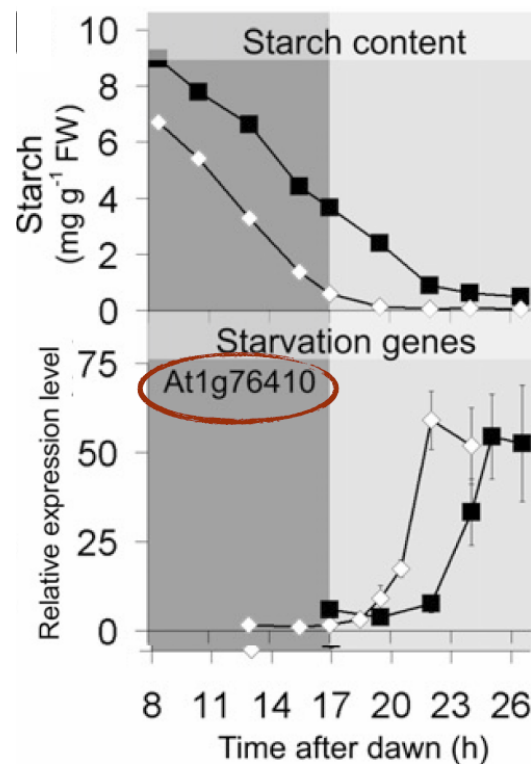
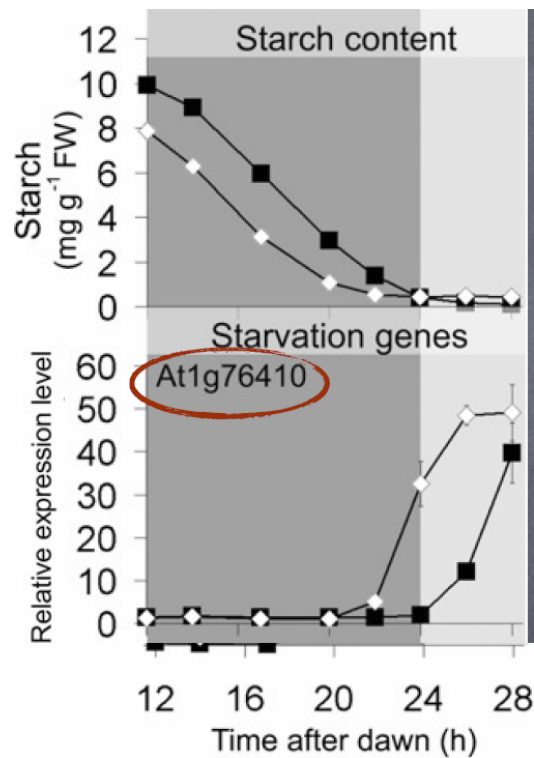
• In *Brachypodium* as well as *Arabidopsis*



Time measured through circadian clock

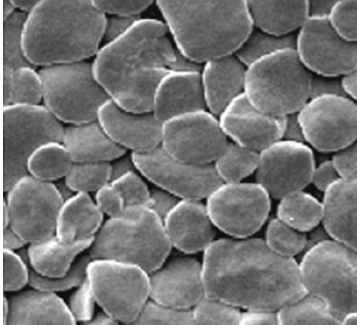
■ wild type

◇ clock *cca1/lhy* mutant (17hr free-running period)



At1g76410 expressed in response to low sugar levels

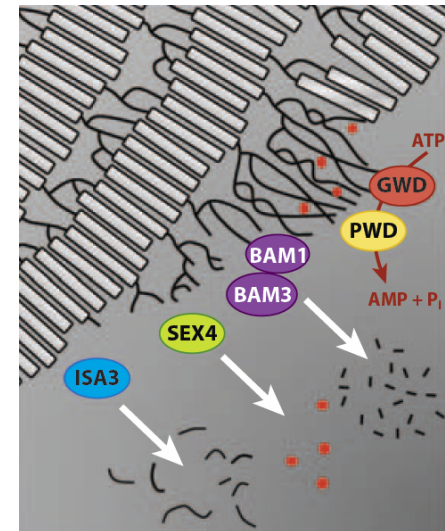
Starch is stored in granules



2 μ m

SEM from Comparot-Moss et al, Plant Physiol. (2010)

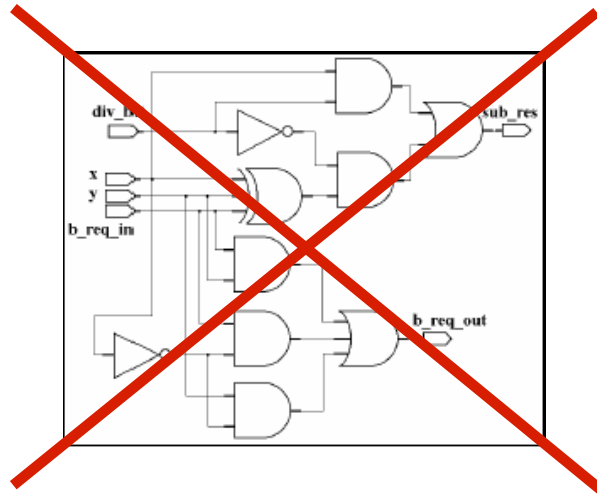
- *Arabidopsis* cells contain starch granules
- Semi-crystalline arrangement inside granule
- Degradation takes place at granule surface through cycles of phosphorylation-degradation-dephosphorylation



Zeeman et al, Ann. Rev. Plant Biol. (2010)

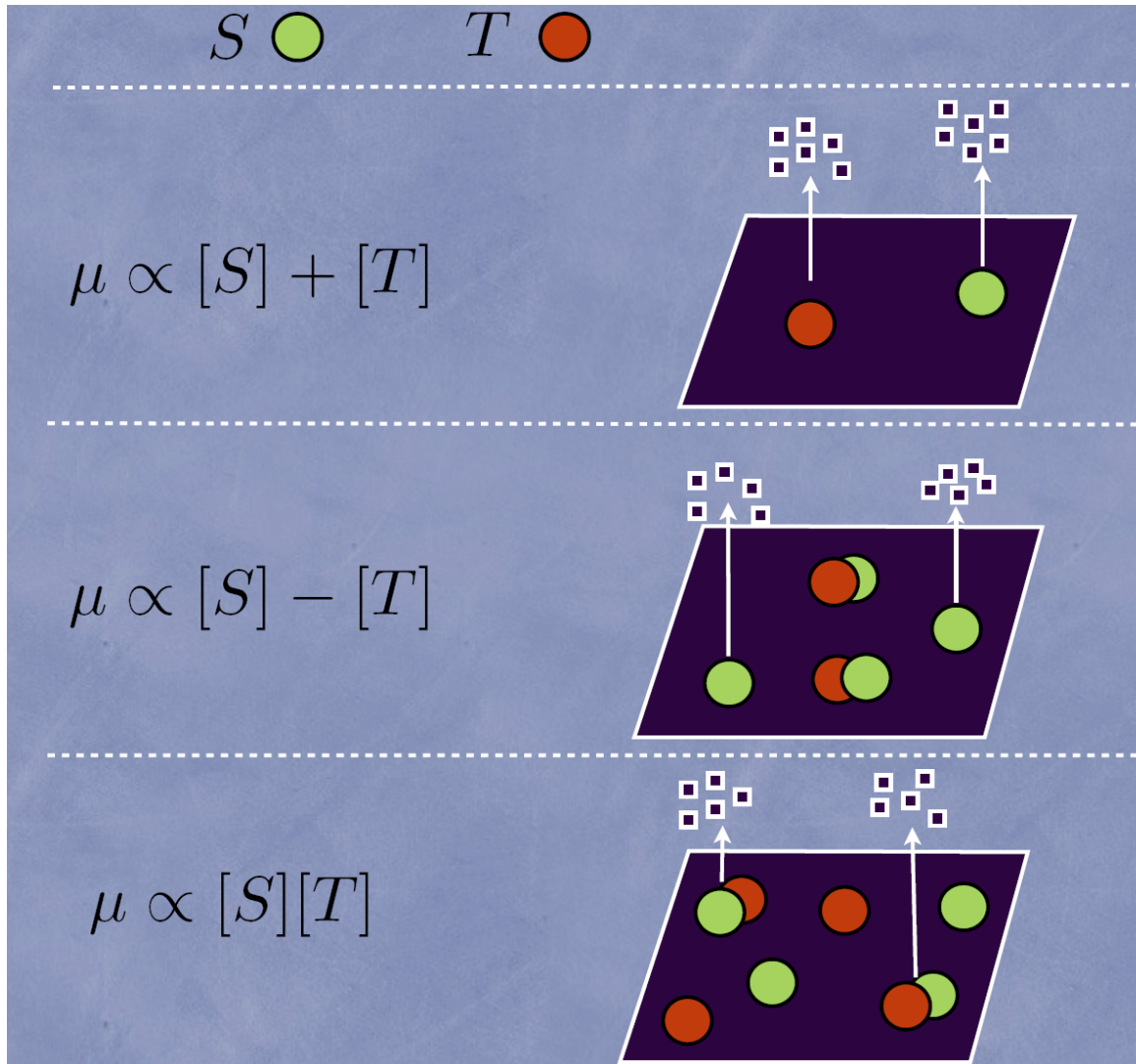
How to implement arithmetic division

- Like a computer, digitally?



- Complex! Is there a better way?

Implementing analogue arithmetic



Very little work on
analogue arithmetic:
Cory and Perkins,
PLOS Comput. Biol.
2008

Only division
is difficult ...

Implementing analogue arithmetic division

ΔS = Starch accumulated

S molecules: $[S] \propto \Delta S$

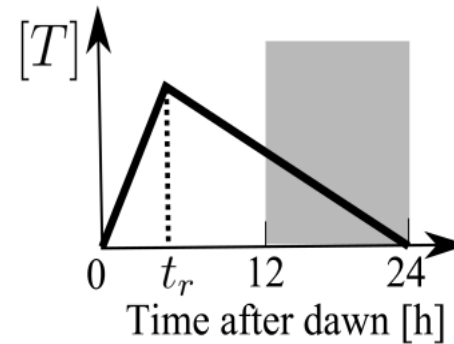
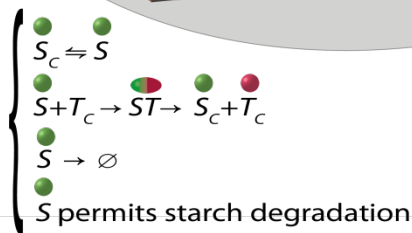
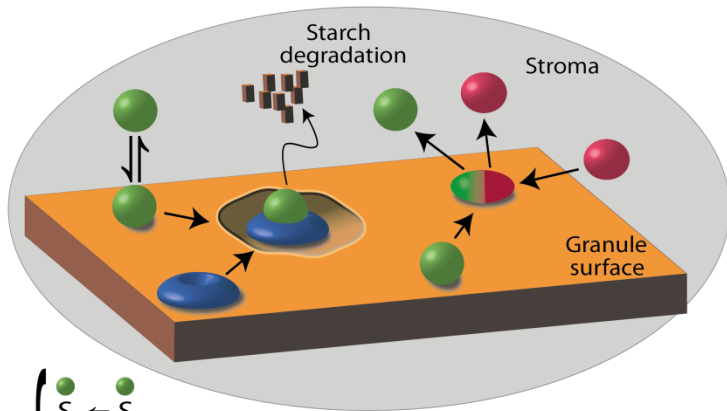
Want starch

Δt = Time to next dawn

T molecules: $[T] \propto \Delta t$

degradation rate:

$$\mu \propto \frac{\Delta S}{\Delta t}$$

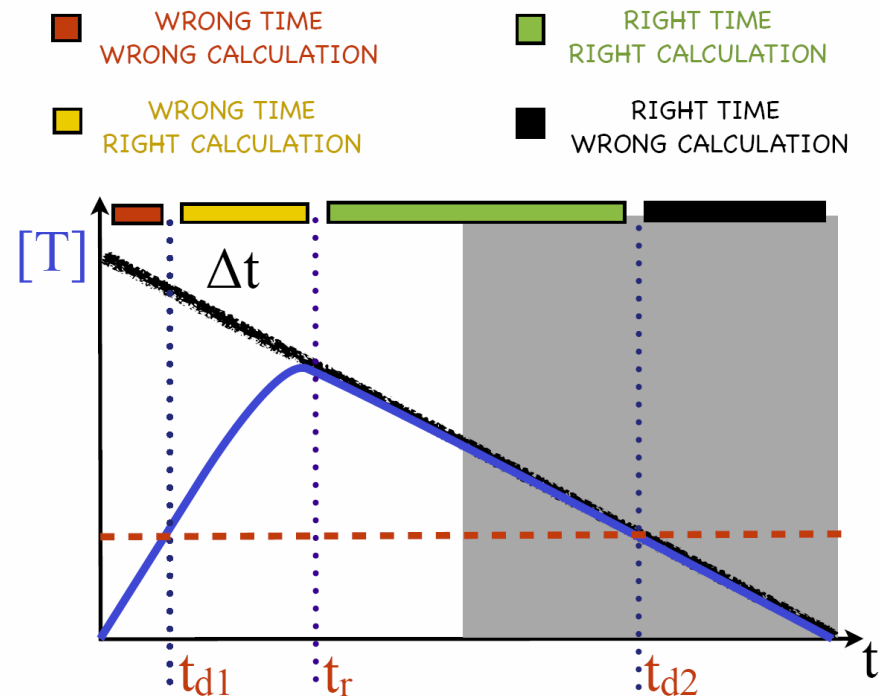


For sufficiently high
[T] concentrations

$$\mu \propto [S] / [T]$$

Correct computation cannot always be performed

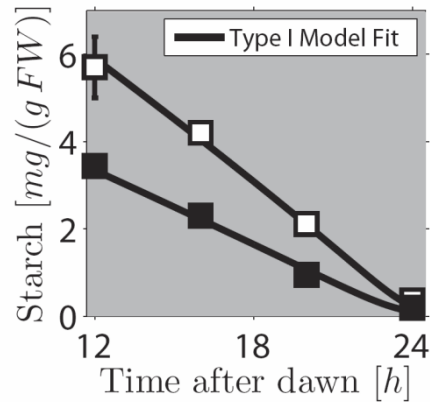
- T molecule level must be reset
- Incorrect computation performed at low [T] levels
- From experiments incorrect degradation rate set if night comes too soon (≤ 8 hrs) after dawn
- So we take the reset time $t_r \approx 6-8$ hrs



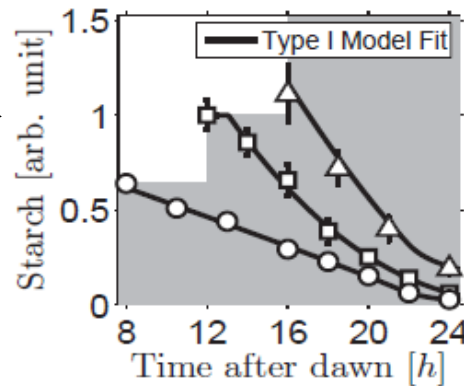
Models fits the data!

Straightforward to fit to ...

Varying daytime light intensity data

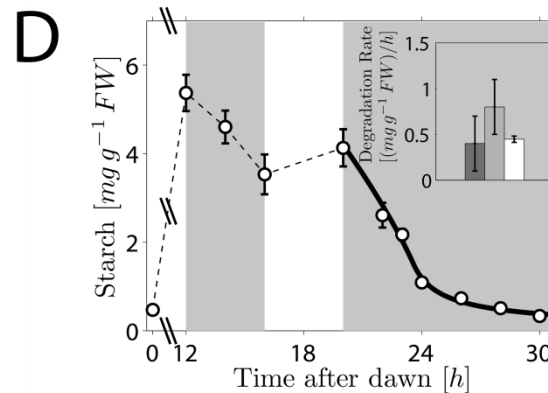
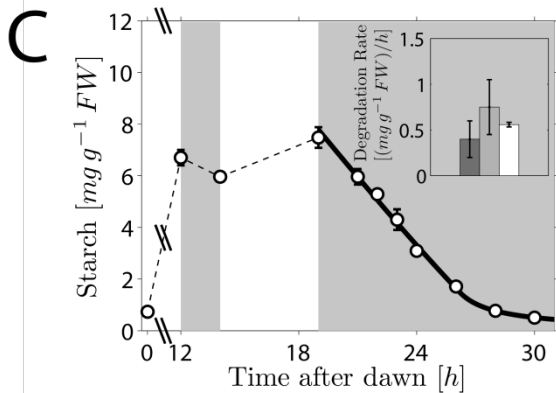
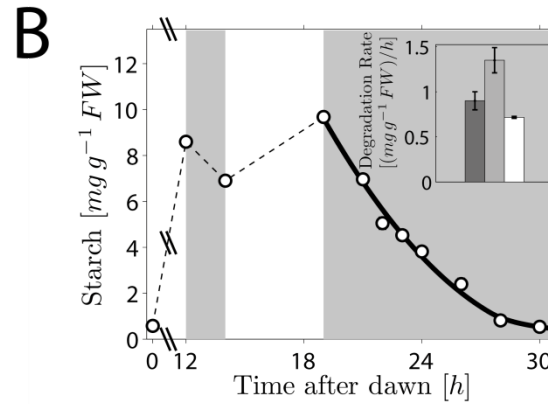
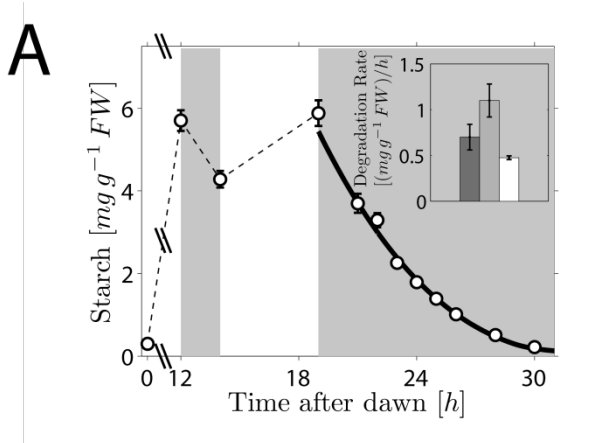


Early or late night onset



But what can we predict?

Degradation rate continuously computed



- Degradation rate faster after night time light period

Conclusions

- **Plants:** not as dumb as you thought!
- **Starch degradation** dynamics appears to encode analogue arithmetic division
- **Mathematical modelling** makes clear prediction about starch dynamics during perturbed night
- Experiments verify model predictions
- Modelling vital for synthetic biology: we can't engineer what we don't understand
- Arithmetic division needed when finite resource needs to be used up in a given time: **hibernation, migration ...**



[Cambridgeshire bird club website](#)



Acknowledgements

Martin Howard group:

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Doreen Feike



Clock is not severely perturbed by light during expected night

Expression of clock genes mostly unaffected by night-time light pulse

