Synthetic Biology Research to Reengineer Biology

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Davidson College Biology and **GCAT**

DAVIDSON

Rhodes College
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Outline of Presentation

What is synthetic biology?

Can intro biology students do synthetic biology research?

Is it possible to reengineer natural selection?

Why do research as an undergraduate?

What is Synthetic Biology?

Implementation of engineering principles and mathematical modeling to the design and construction of biological parts, devices, and systems with applications in energy, medicine, and technology.

www.bio.davidson.edu/projects/gcat/Synthetic/What_Is_SynBio.html

Synthetic Biology

Genetic engineering on a new scale.

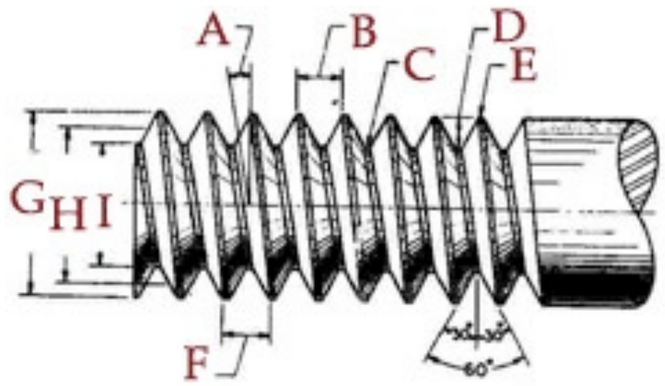
Four Characteristics:

- Standardization
- Modularity
- Abstraction
- Modeling of Designs

Standardization

On a Uniform System of Screw Thread

"In this country, no organized attempt has as of yet been made to establish any system, each manufacturer having adopted whatever his judgment may have dictated as best, or as most convenient for himself."



William Sellers April 21, 1864

http://openwetware.org/images/b/bd/BBFRFC9.pdf

Standardization

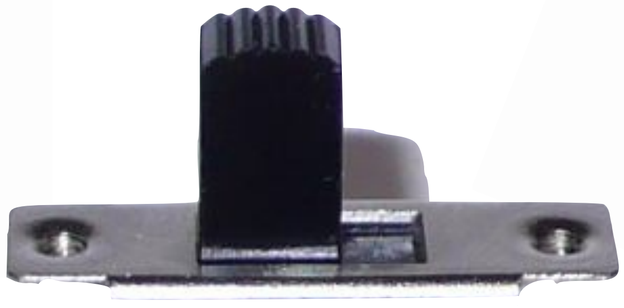
On a Uniform System of Screw Thread

Modularity

USB ports on computers

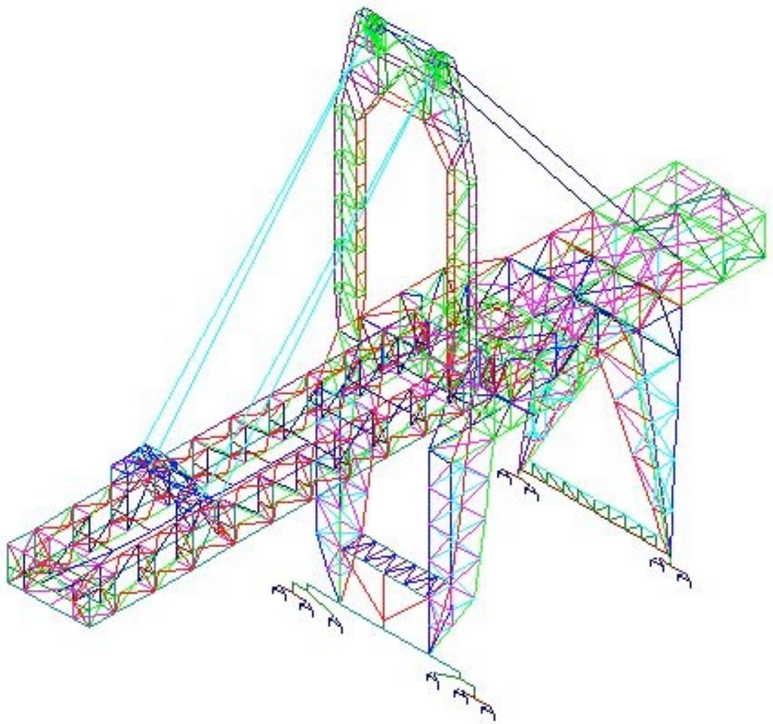
Modularity

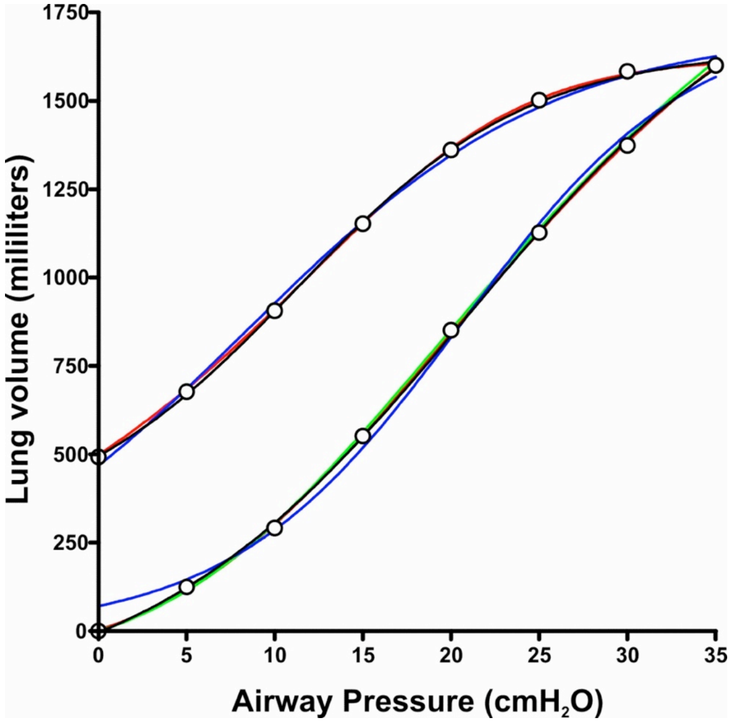
Abstraction

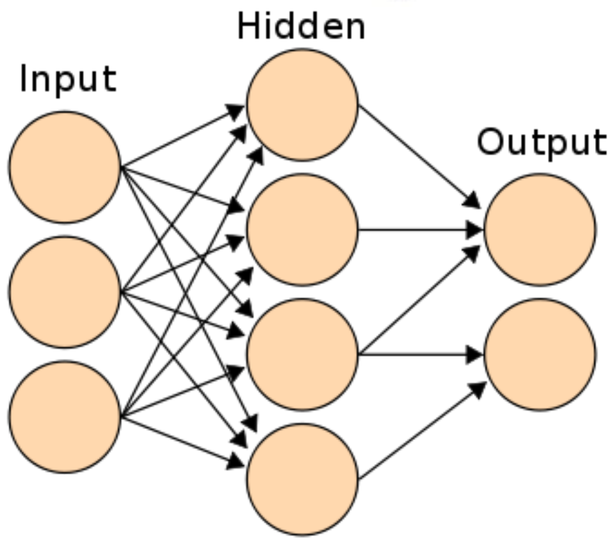


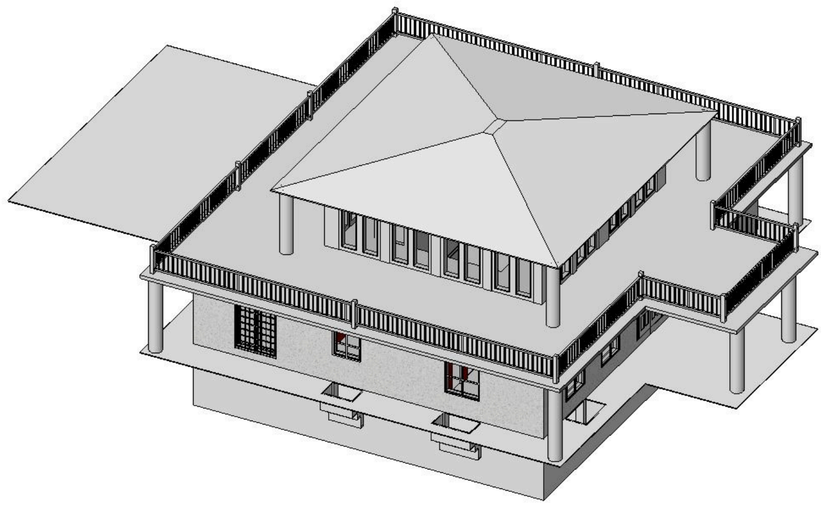
Abstraction

Modeling of Designs

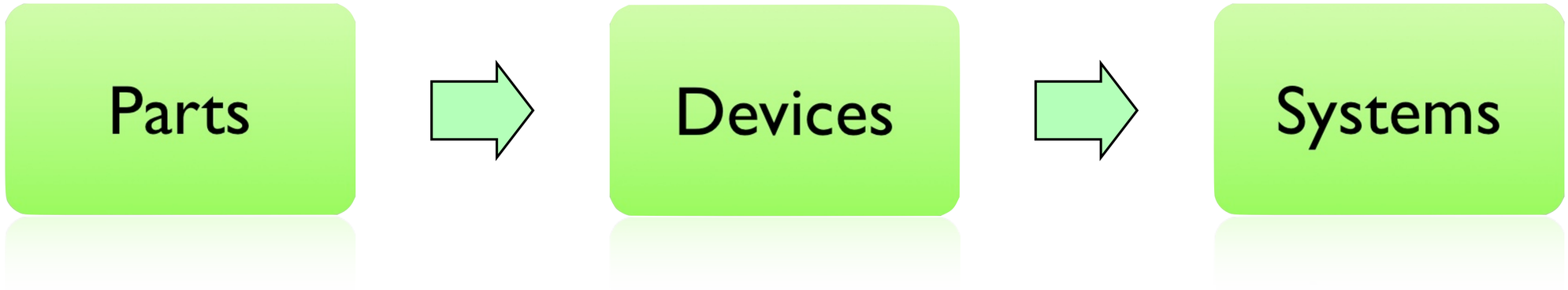






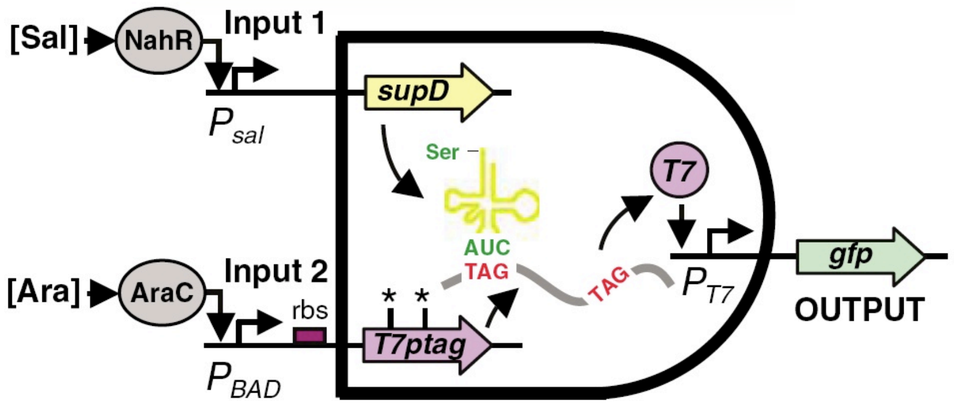


Synthetic Biology



Synthetic Biology

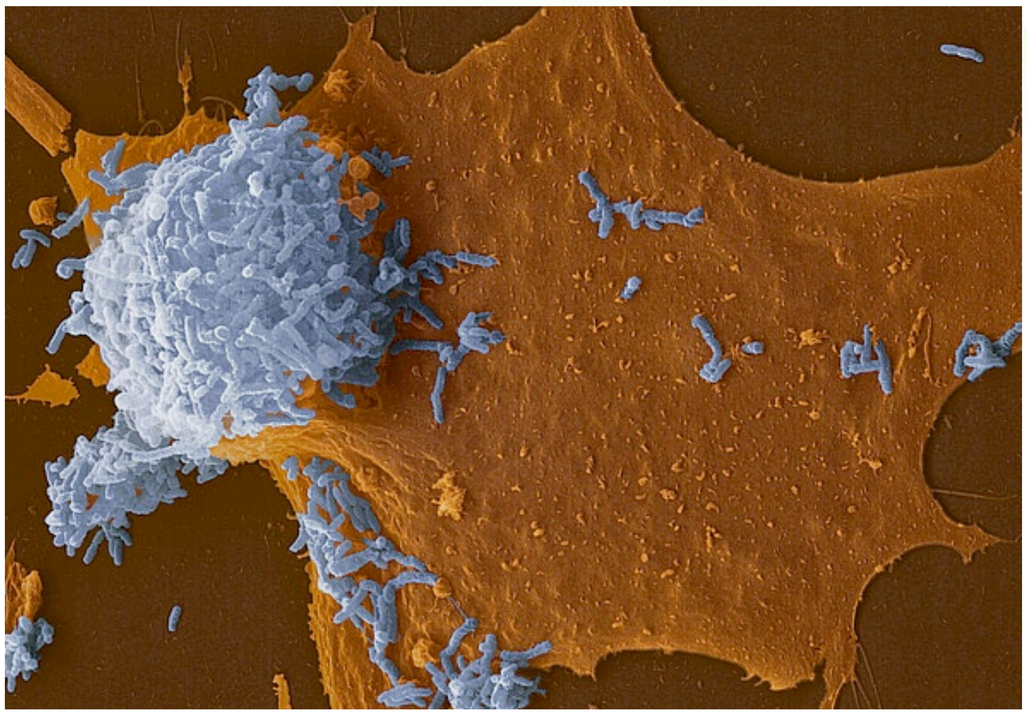
Synthetic Biology



Anderson *et al. Mol Sys Bio*. 2007.

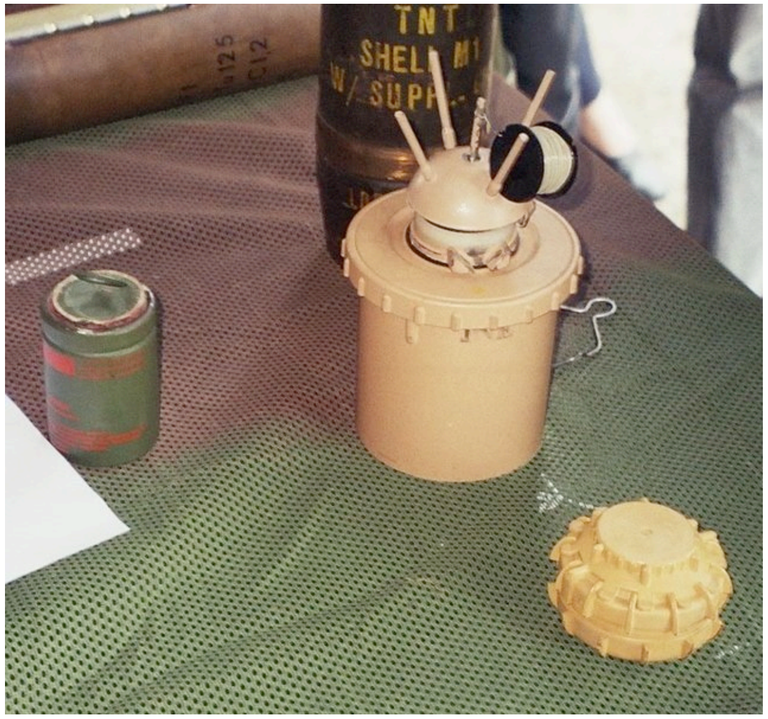
Synthetic Biology

Parts → Devices → Systems

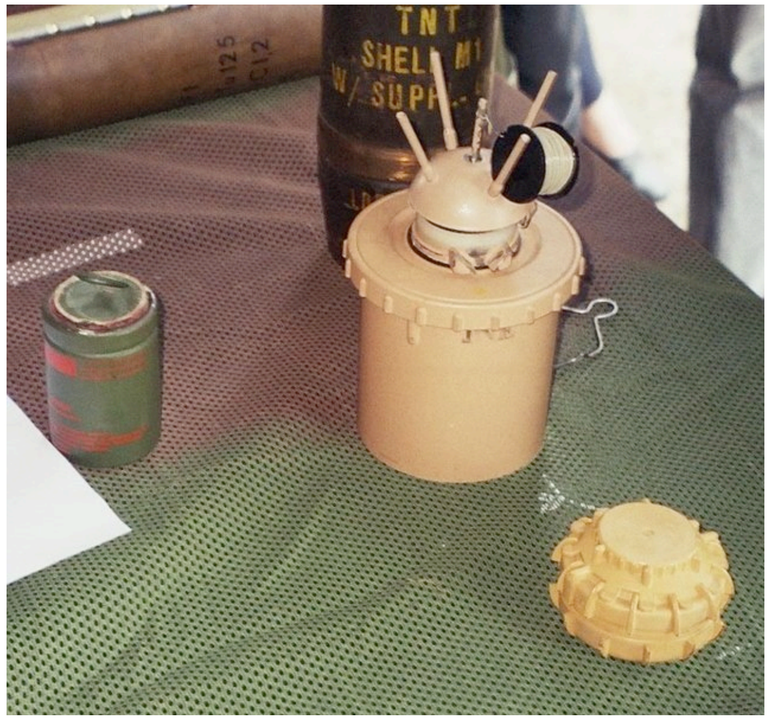


Real World Applications of Synthetic Biology

Land Mine Detection



Land Mine Detection



Synthetic Biology
Land Mine Detection

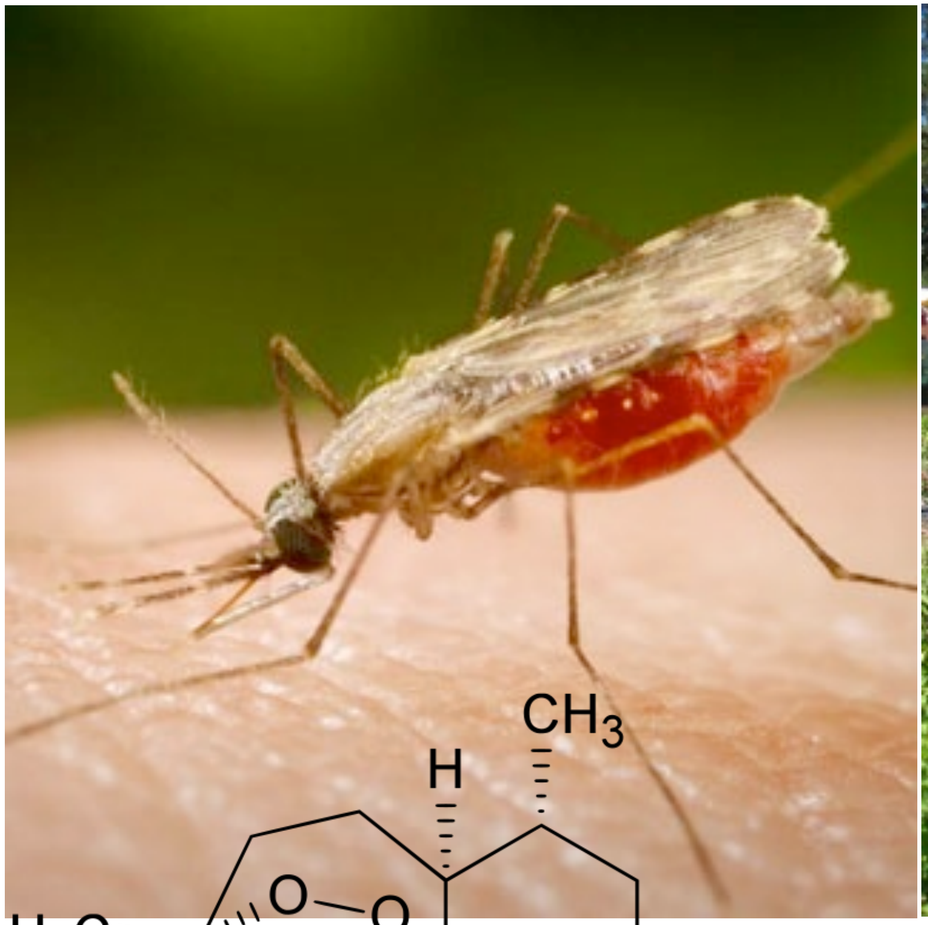
WARNING SIGN: The bioengineered Thales cress turns red when exposed to a mine byproduct.

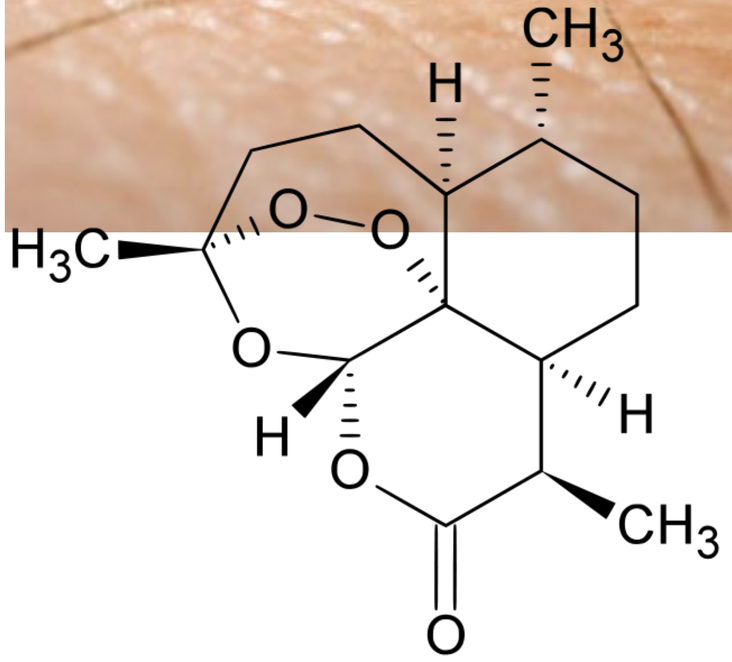
COURTESY OF ARESA BIODETECTION

New weed may flag land mines

By John K. Borchardt | *Contributor to The Christian Science Monitor*

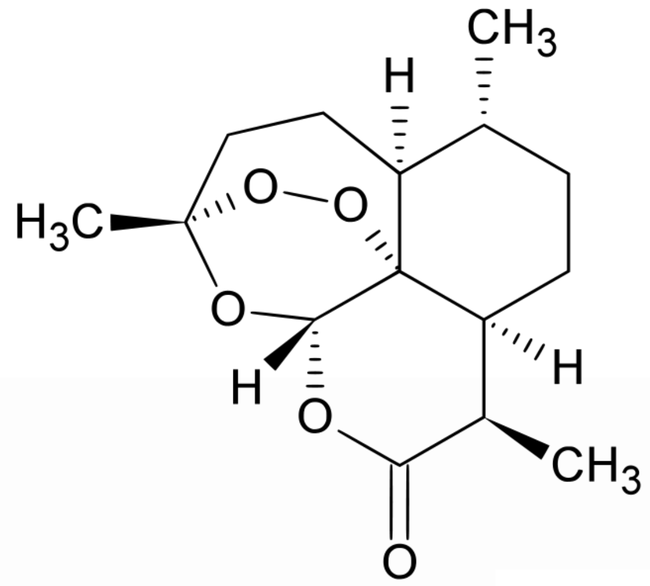
Production of Medicines



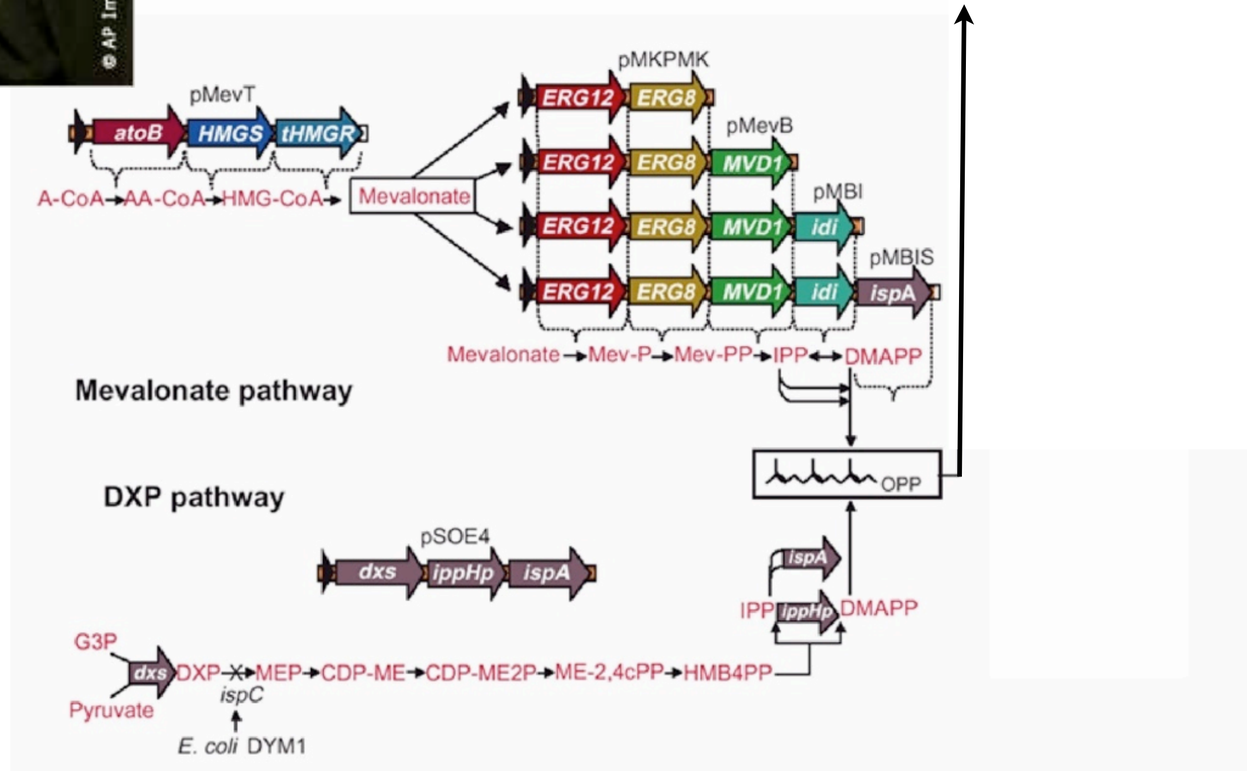


$1 per pill

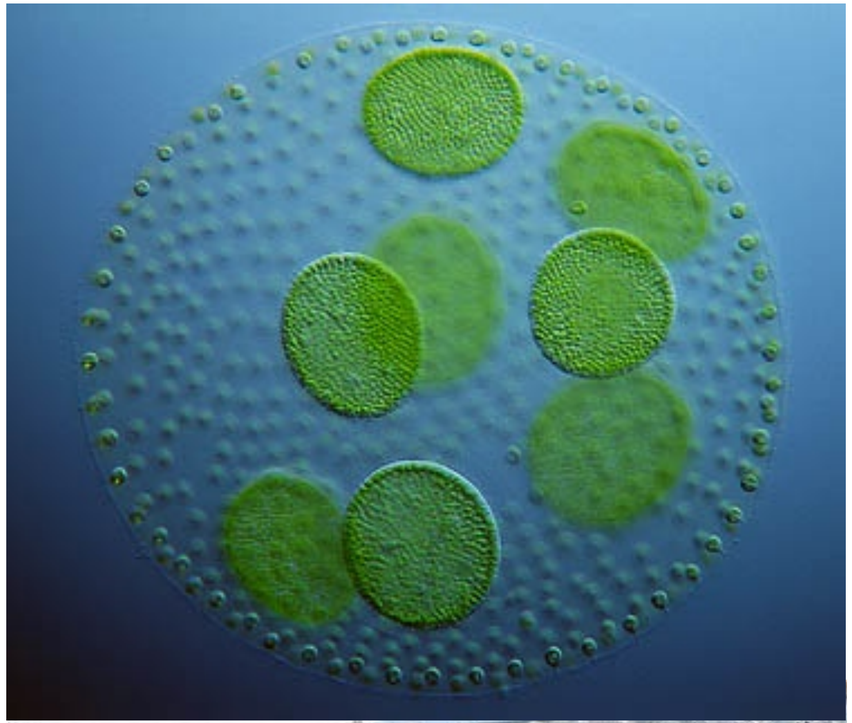
Production of Medicines



10¢ per pill



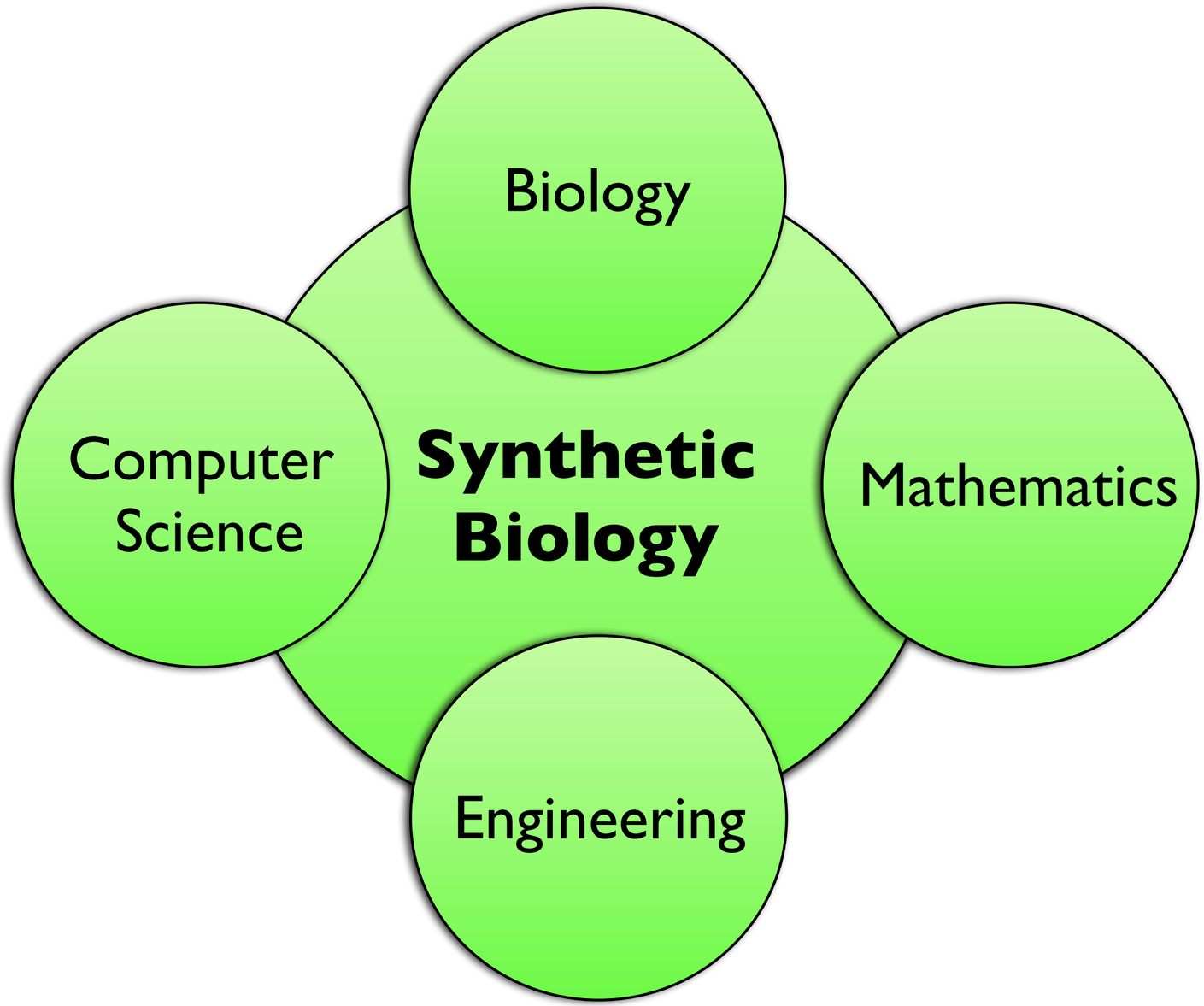
Biofuels from Algae



CO_2-neutral

1,000,000 gallons in 2008

Synthetic Biology



Intro Bio Students Conduct Promoter Research Using Synthetic Biology

Eco RI

GAATTC
CTTAAG

palindrome

type II

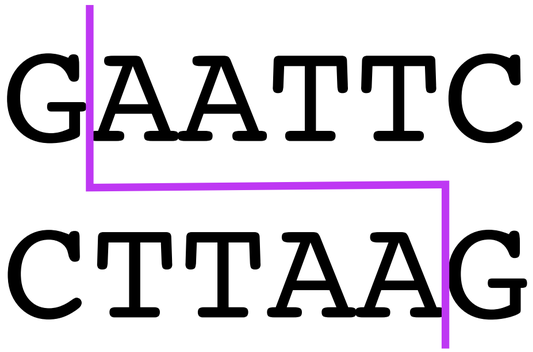
Eco RI

GAATTC
CTTAAG

palindrome

type II

Eco RI



type II

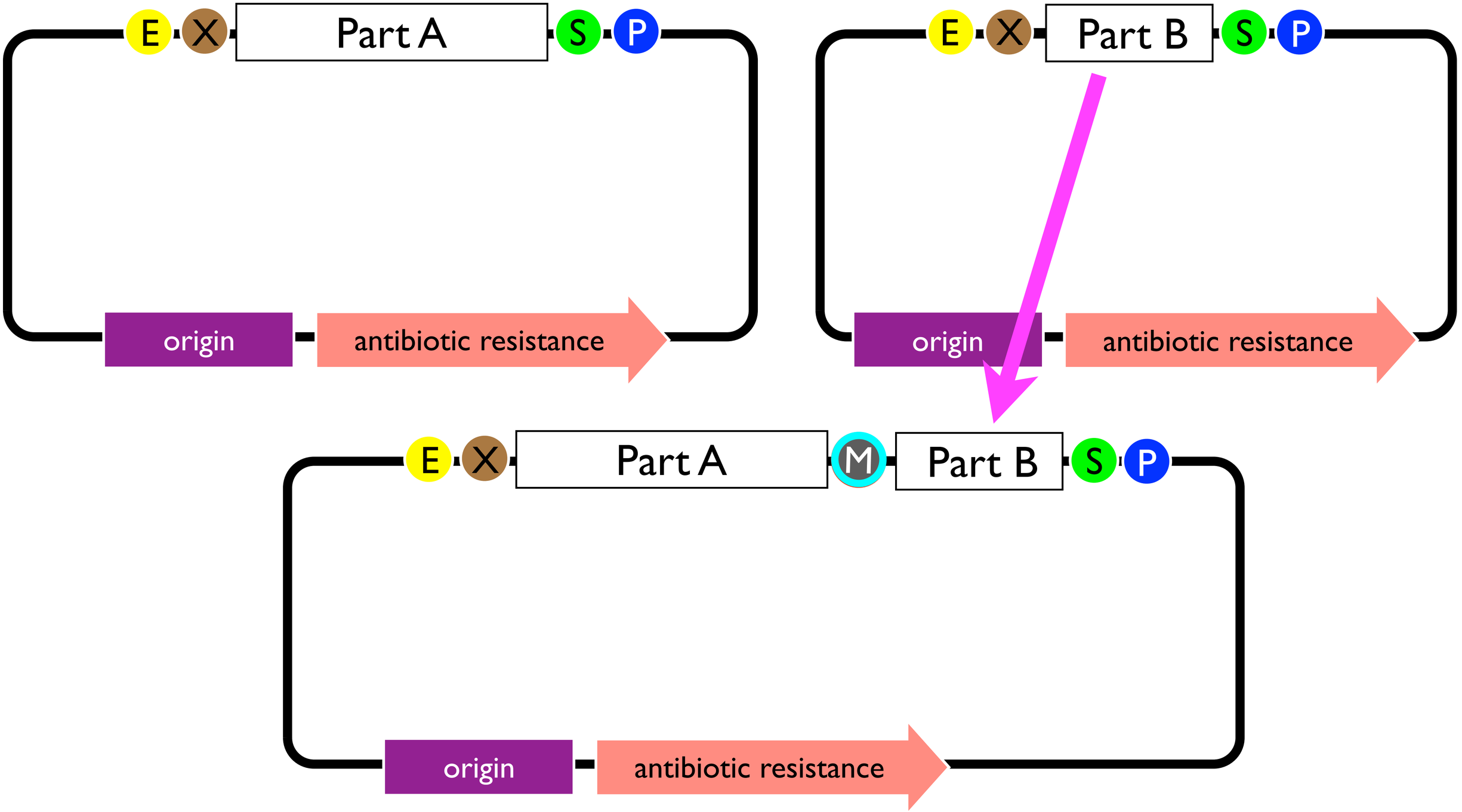
Eco RI

G AATTC

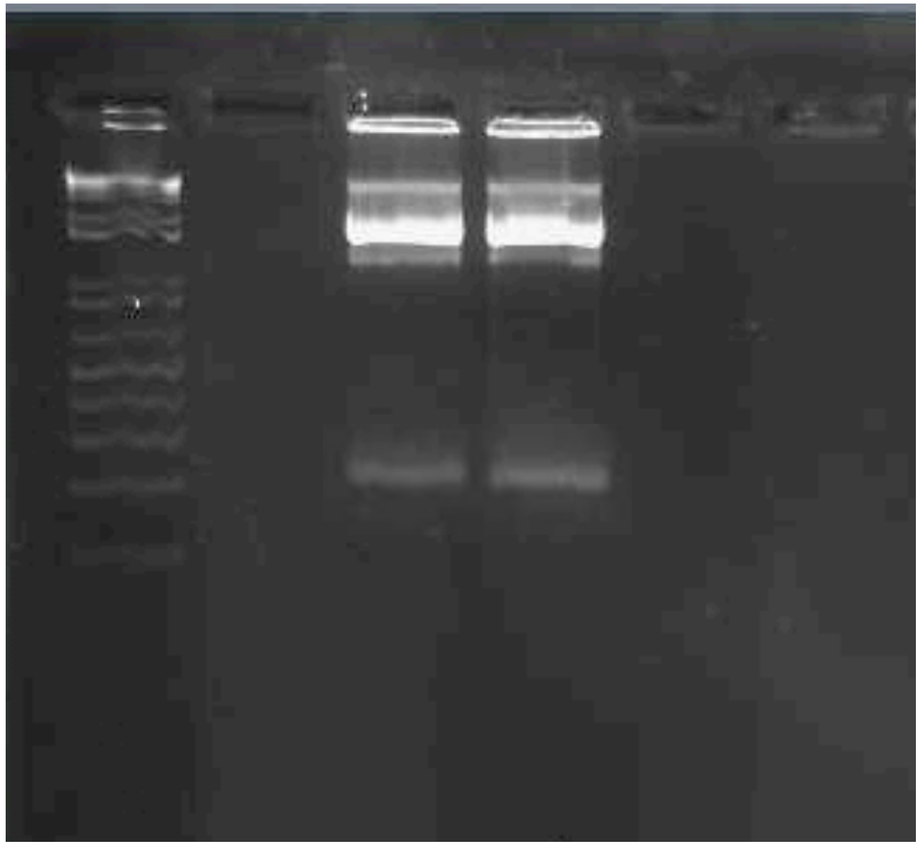
CTTAA G

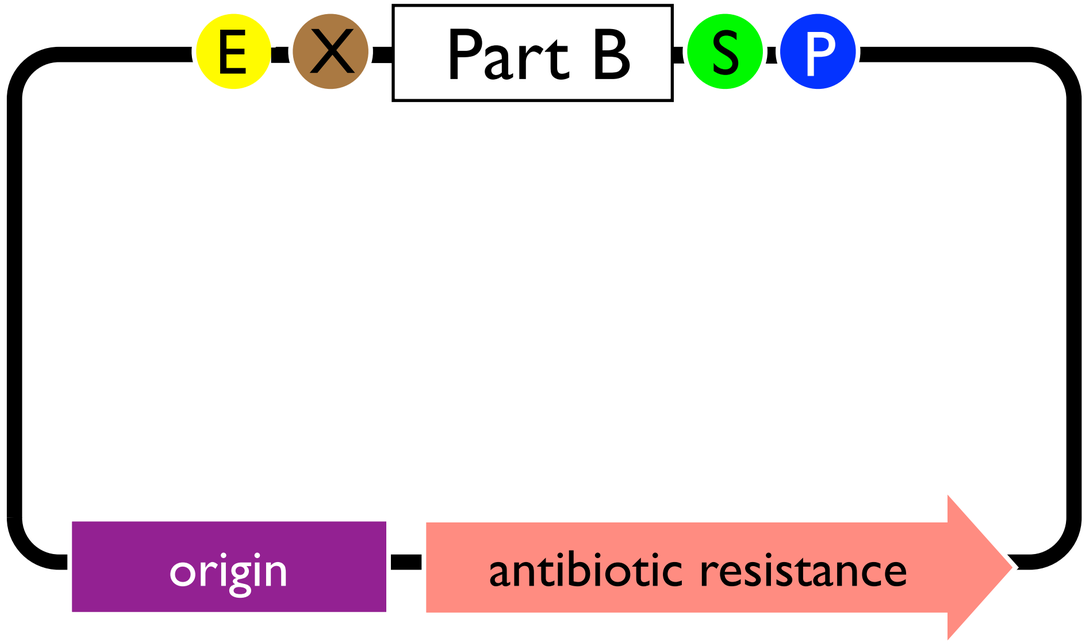
type II

Traditional Cloning (type II)

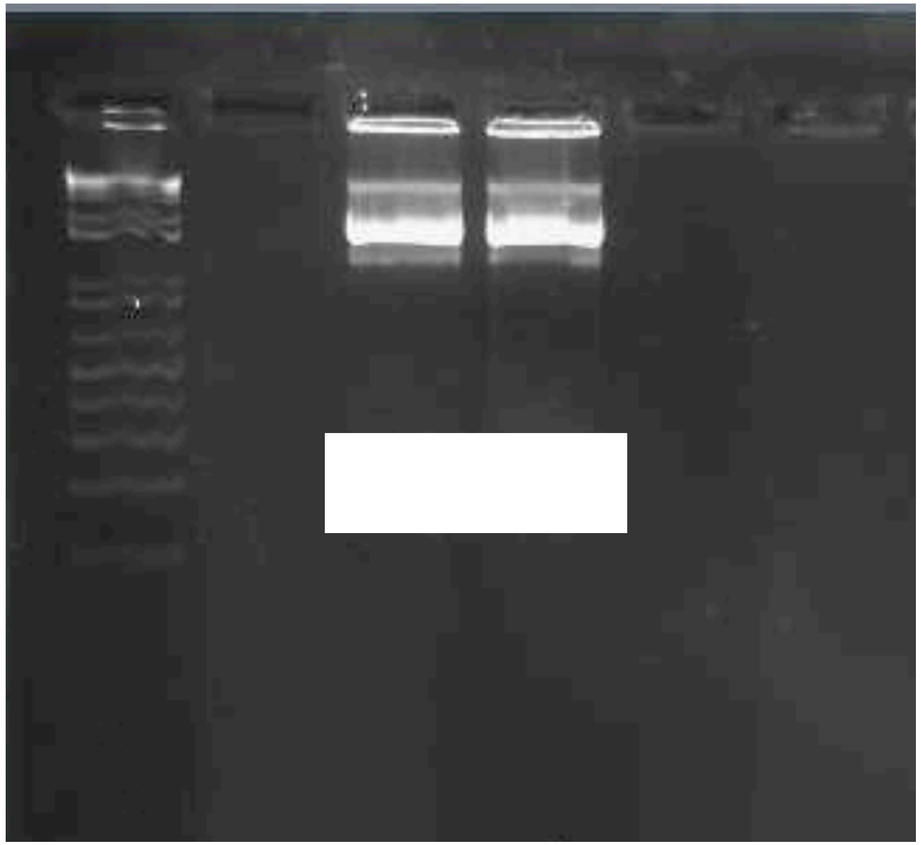


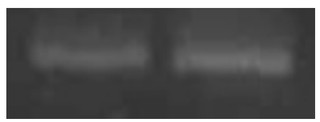
Gel Purification

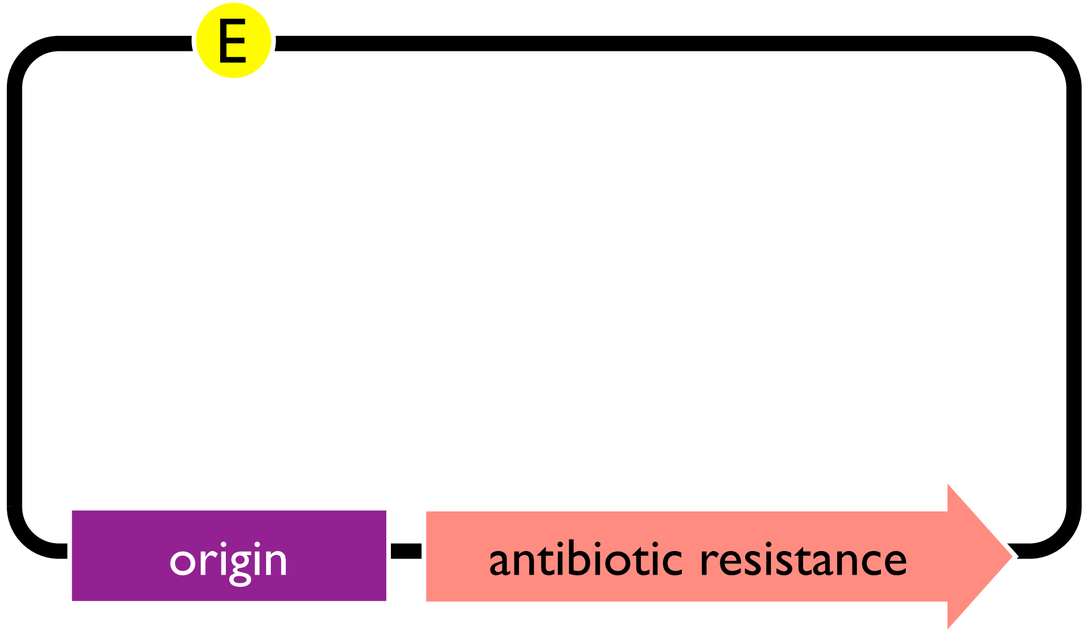




Gel Purification







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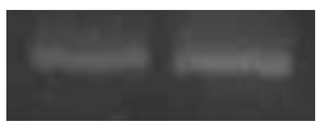

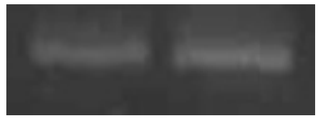

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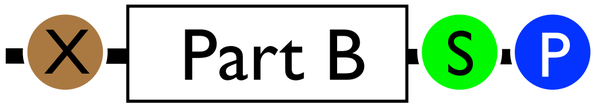

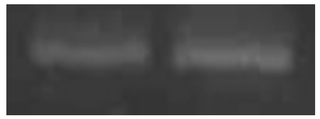

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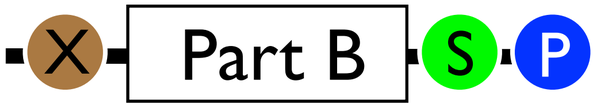
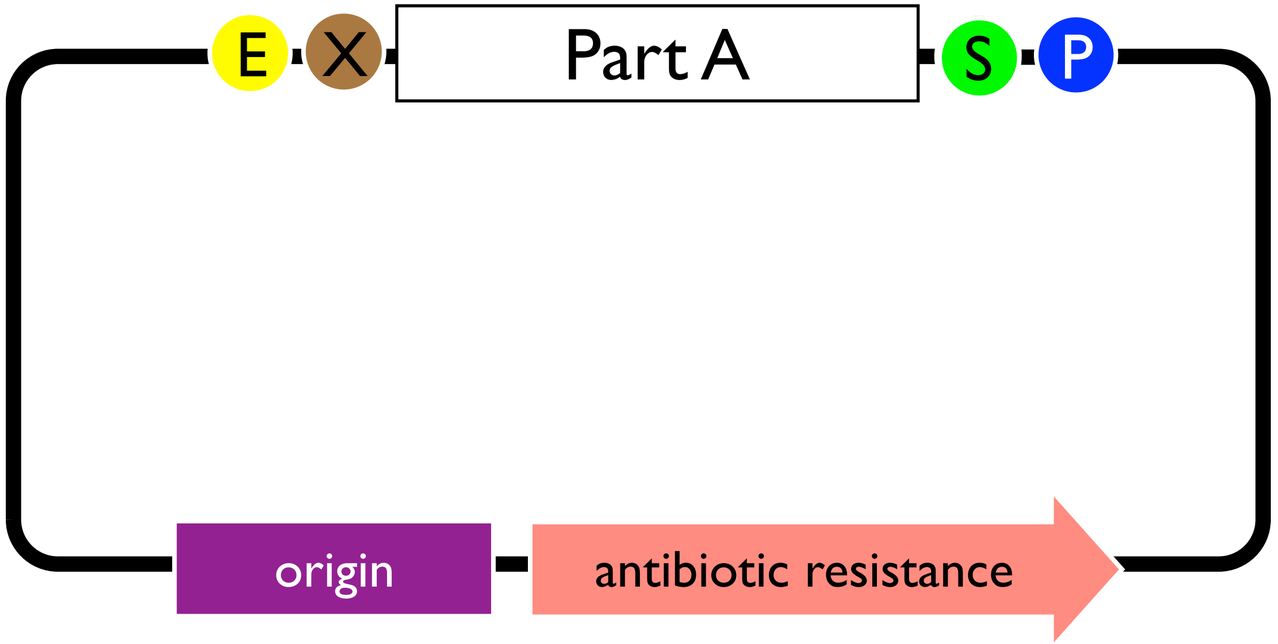
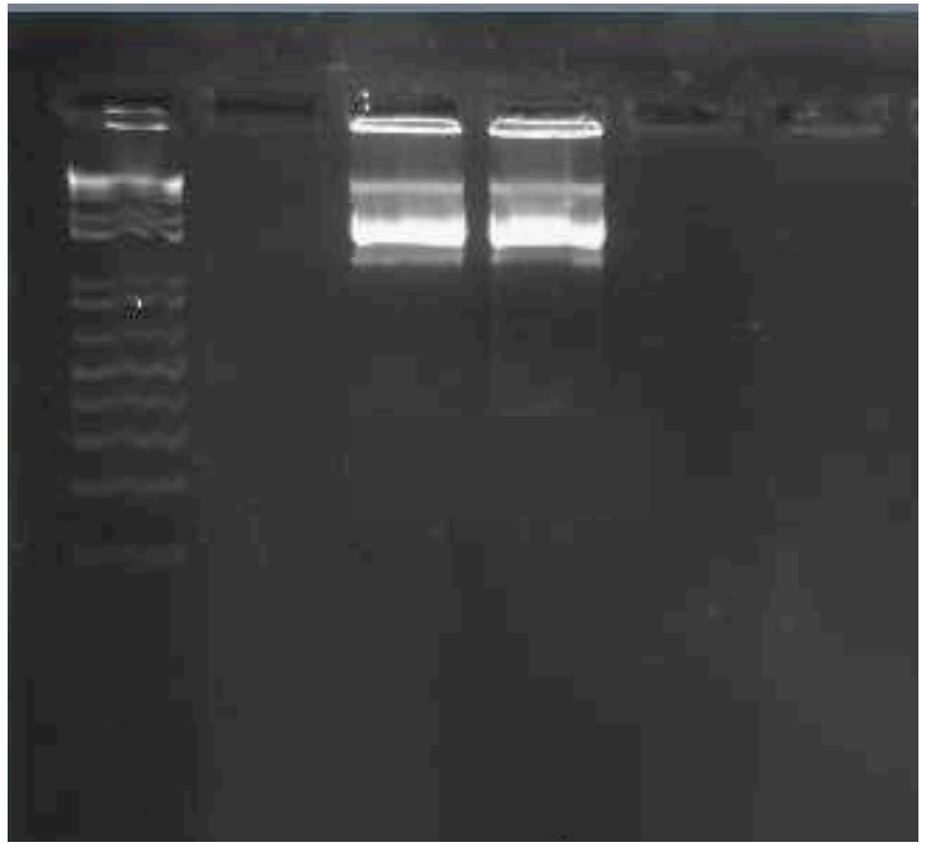
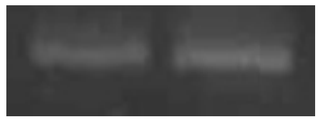


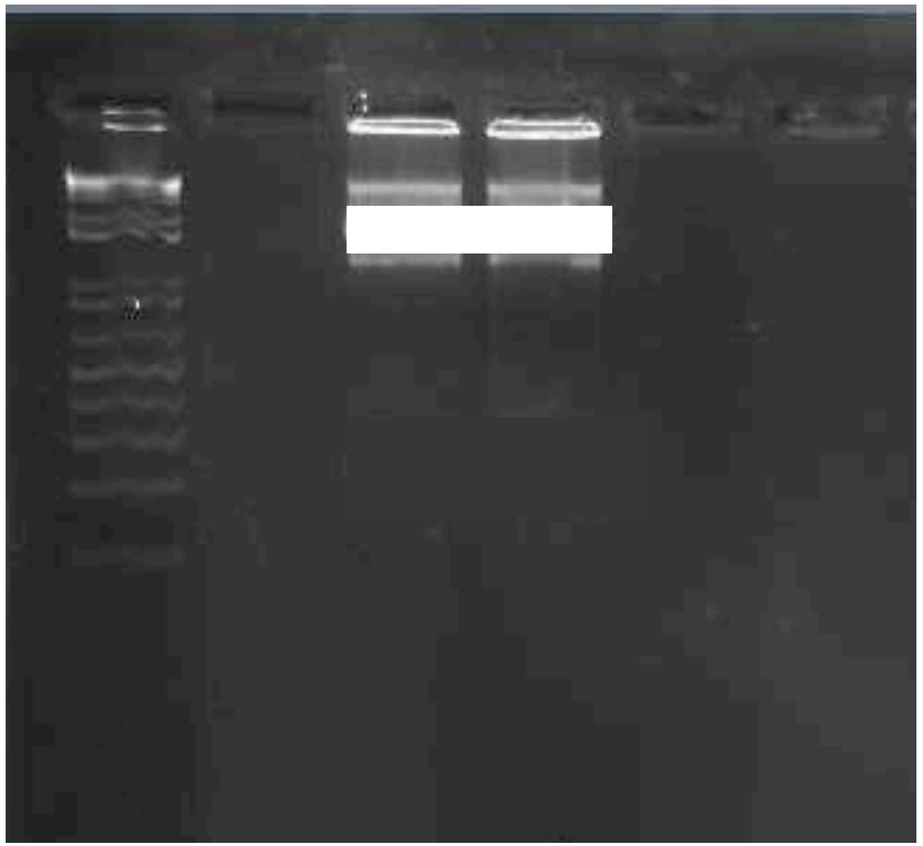






Gel Purification

X Part B S P

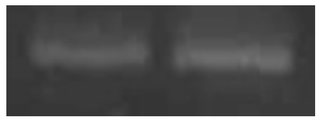


S P

E X Part A S P

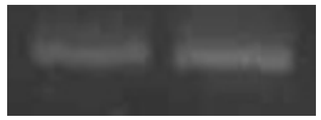
origin

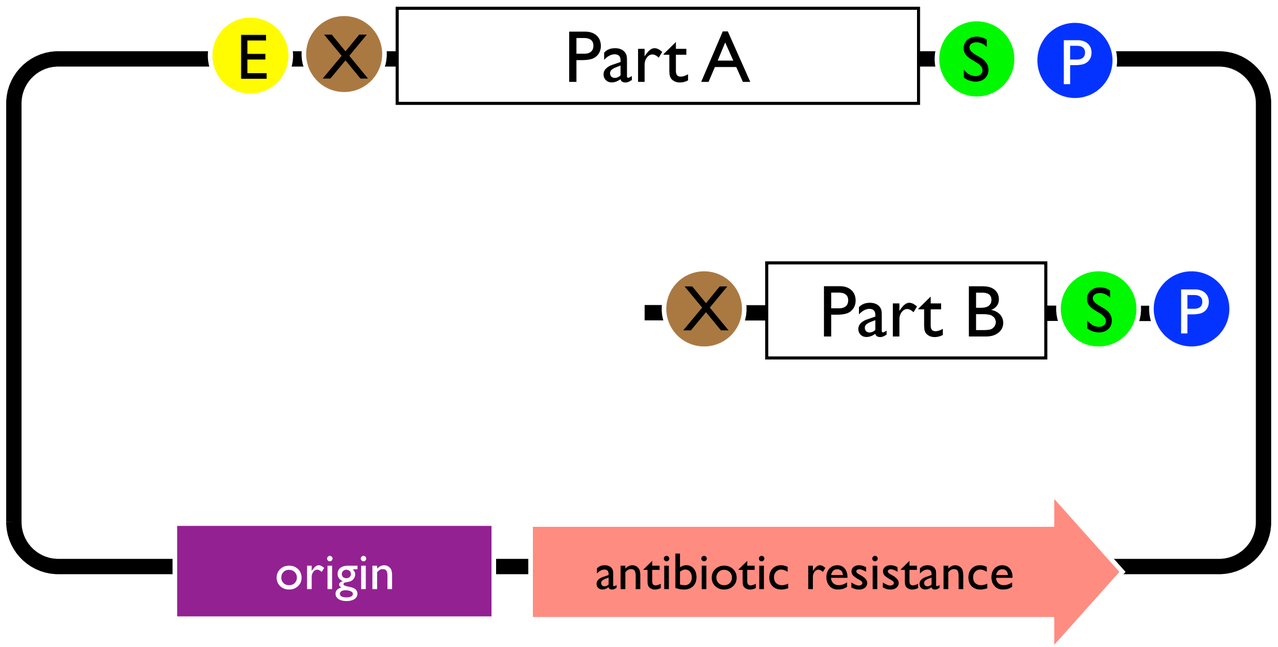
antibiotic resistance



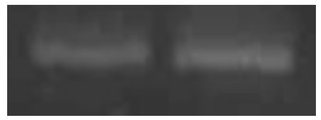
Gel Purification

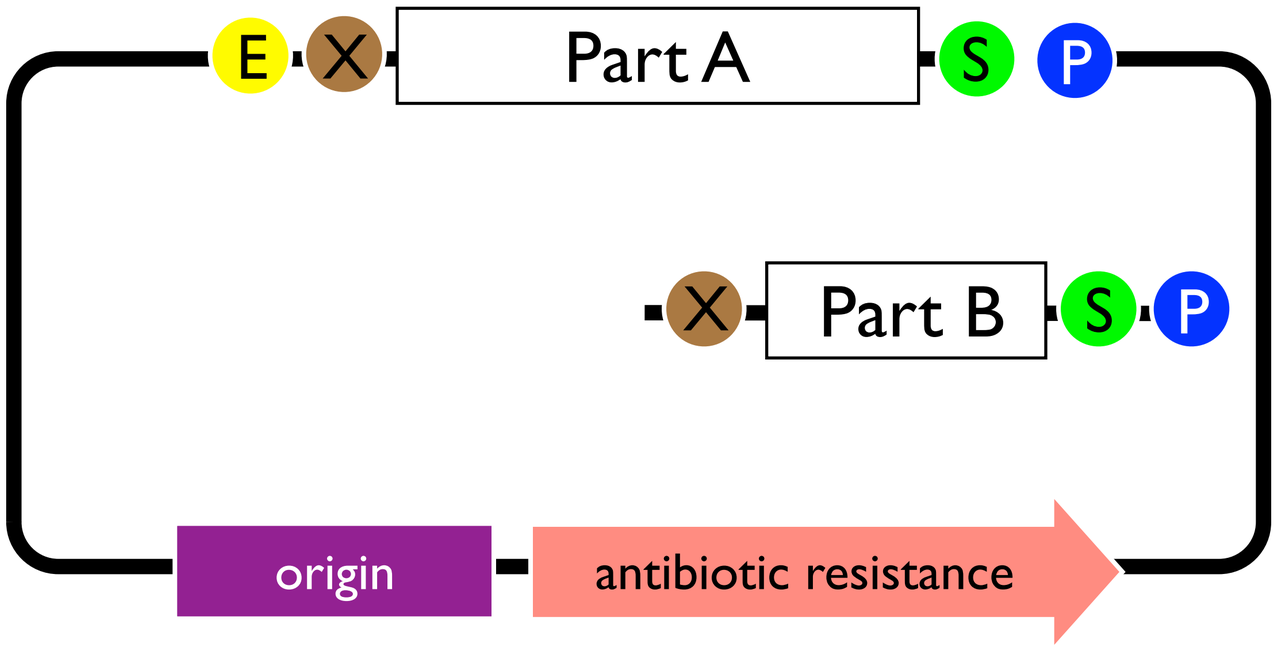
Gel Purification



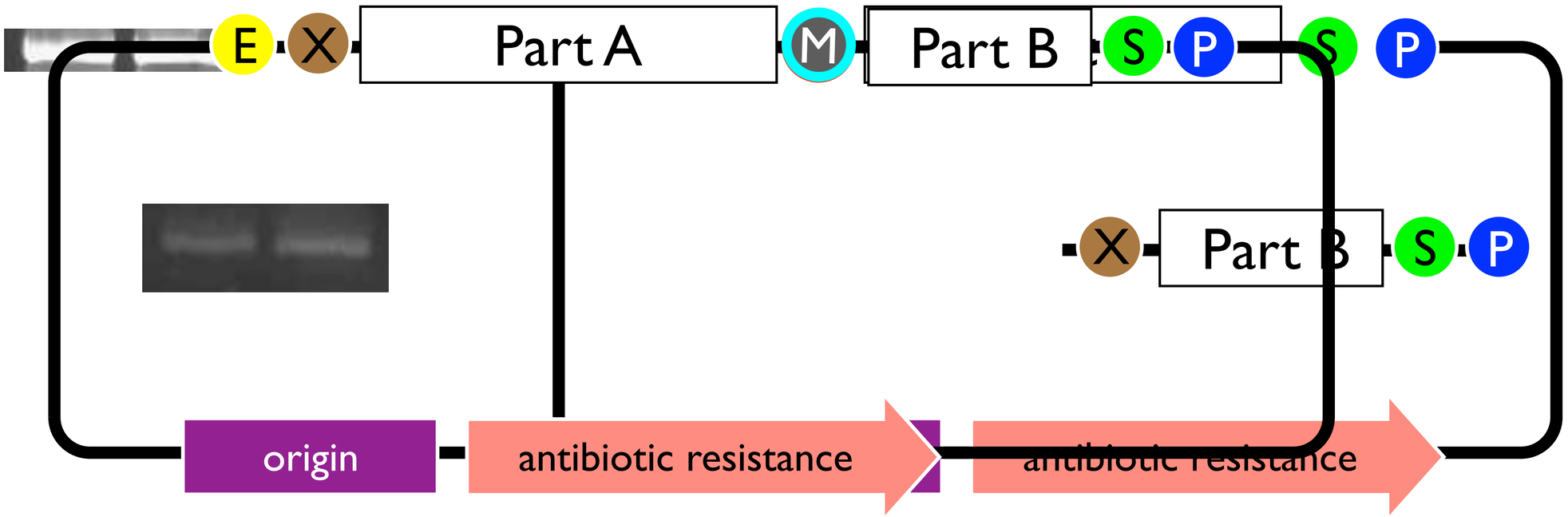


Ligation





Ligation

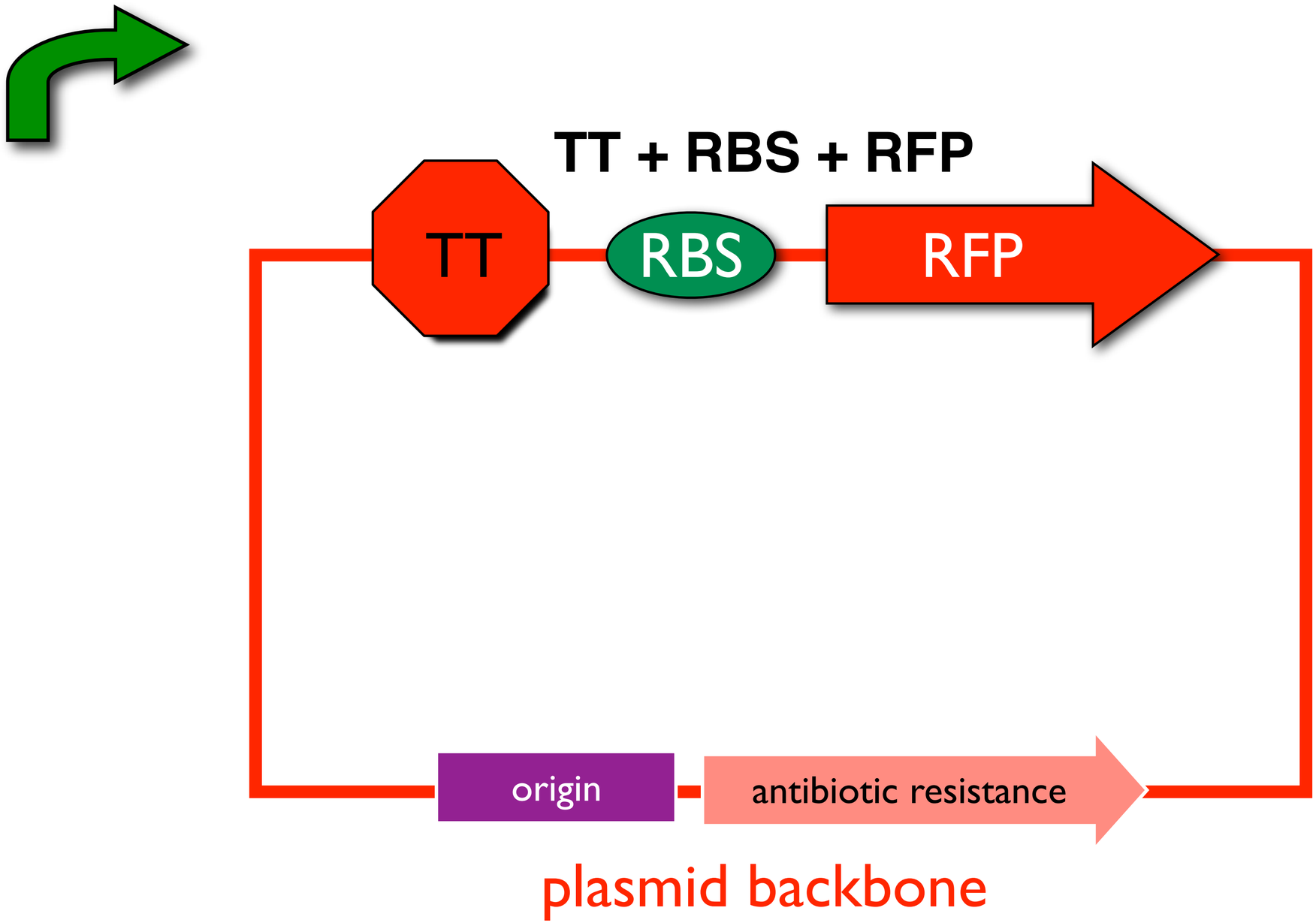

E
X
Part A
M
Part B
S
P
S
P
X
Part B
S
P
origin
antibiotic resistance
antibiotic resistance

How can we clone DNA without all the hassle?

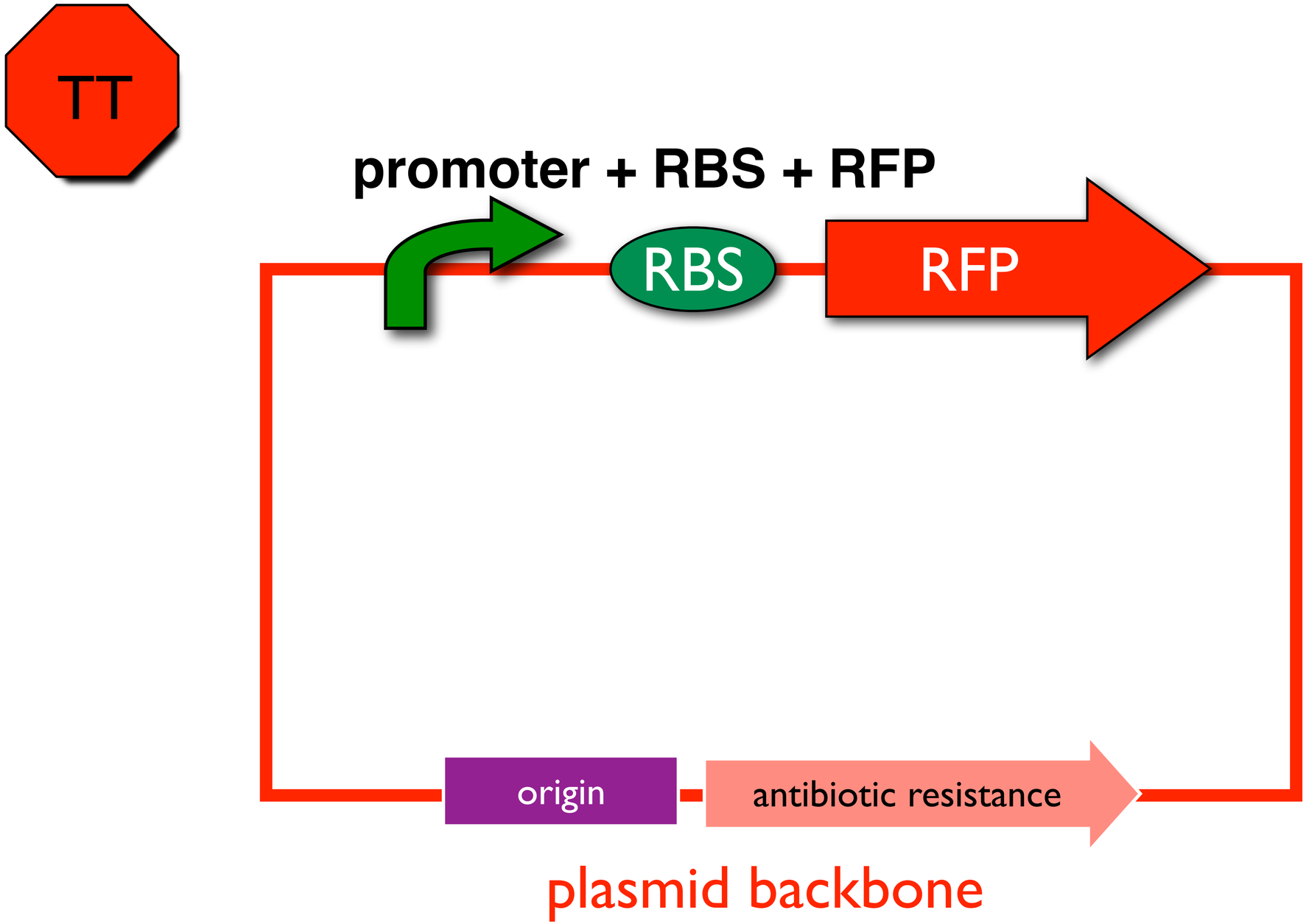
Todd Eckdahl

Discover Gold WESTERN

Golden Gate Assembly Method



Golden Gate Assembly Method



Bsa I

GAGACC

CTCTGG

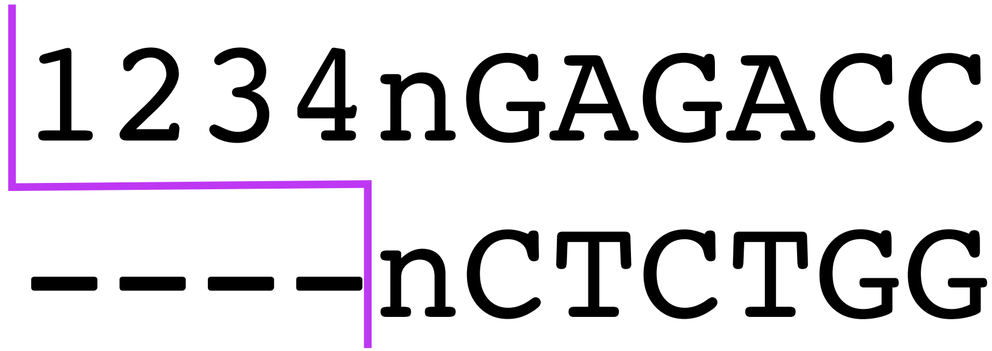
G

not a palindrome

palindrome

type IIs

Bsa I



type IIs

Bsa I

```
1234nGAGACC
----      nCTCTGG
```

type IIs

Bsa I

```
GGTCTCn----
CCAGAGn1234
```

type IIs

Bsa I

```
GGTCTCn                ----
CCAGAGn1234
```

type IIs

Bsa I

cuts left

1234nGAGACC

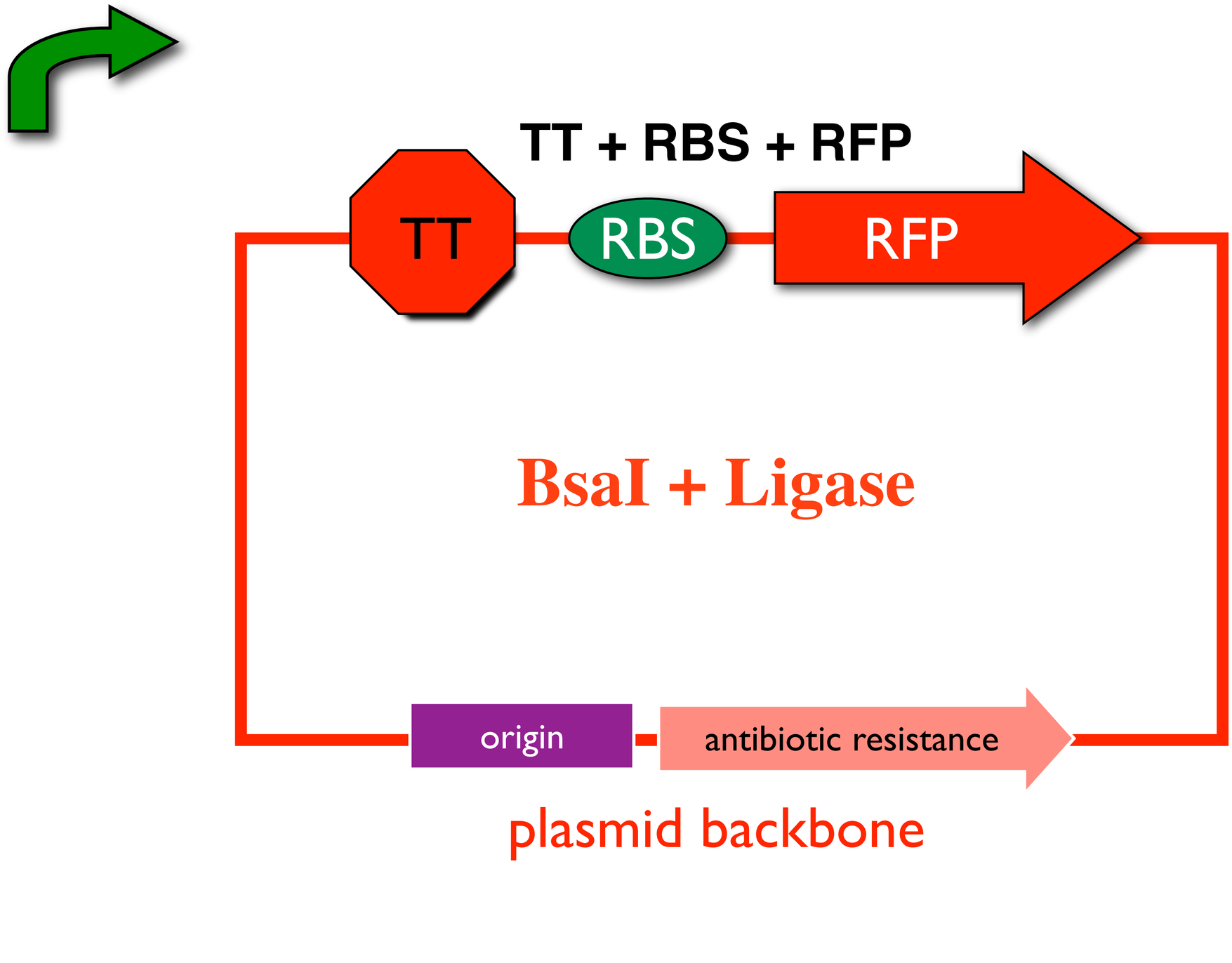
----nCTCTGG

GGTCTCn----

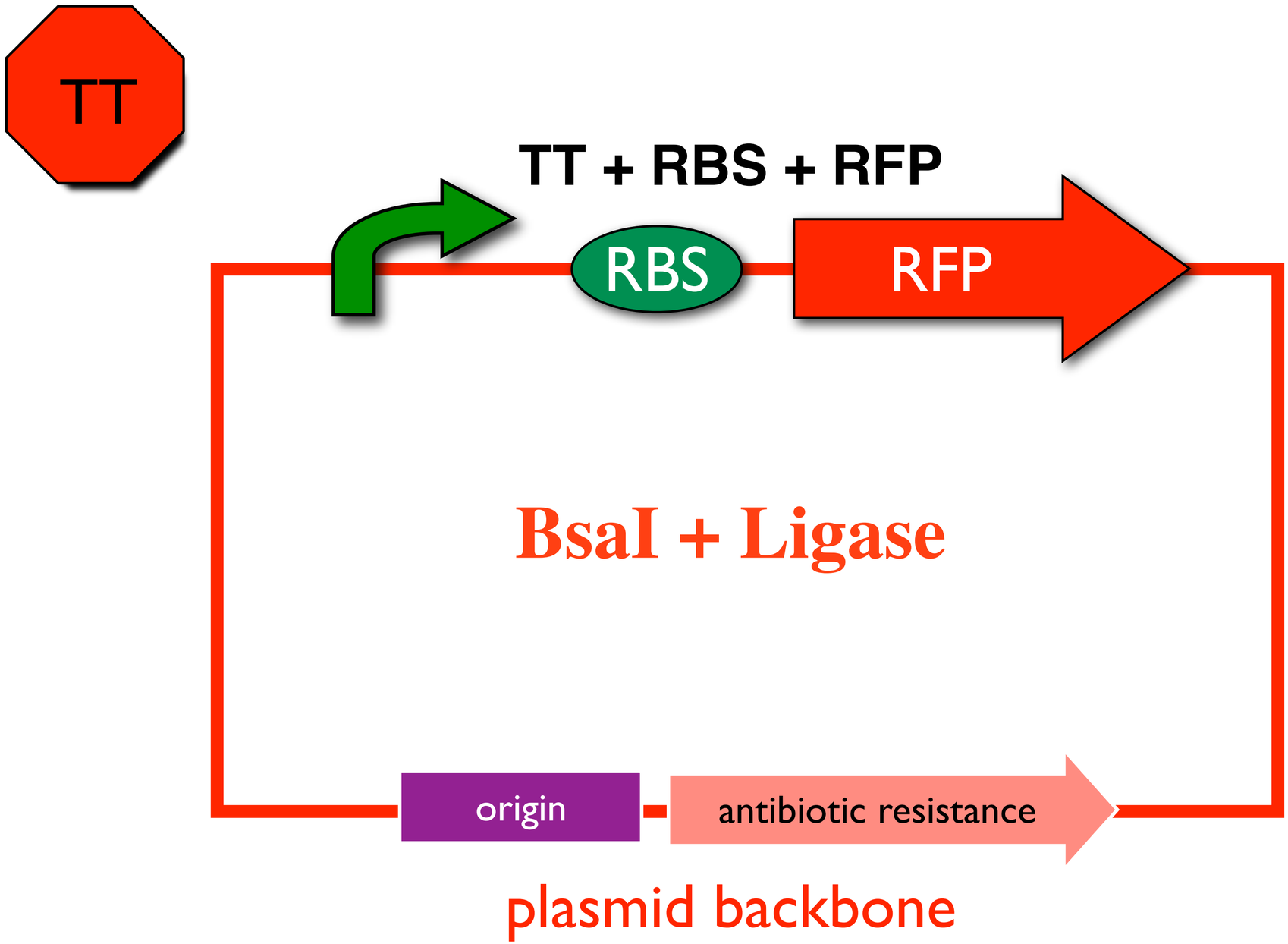
CCAGAGn1234

cuts right

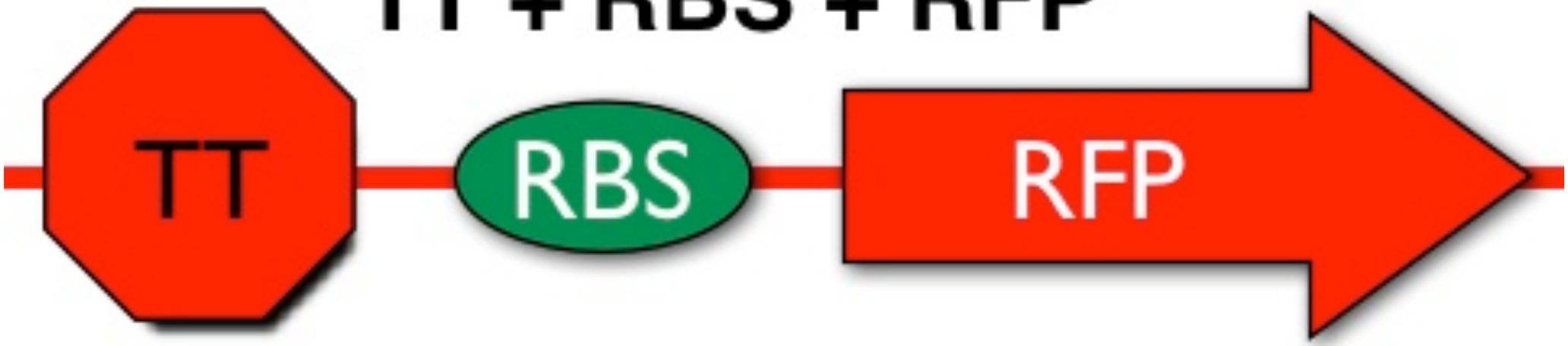
GGA Ligation Method



GGA Ligation Method



TT + RBS + RFP



Bsa I

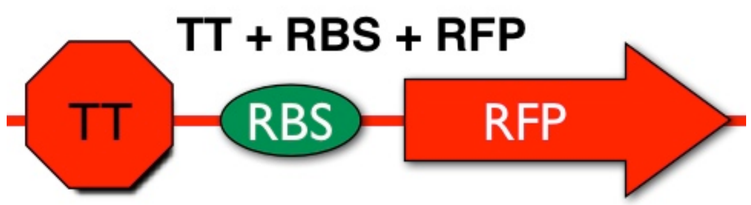
CGACtGAGACC(TT)GGTCTCaGCGG

GCTGaCTCTGG(TT)CCAGAGtCGCC

ligase

Bsa I

ligase



CGACtGAGACC(TT)GGTCTCa

aCTCTGG(TT)CCAGAGtCGCC

[redacted]

[redacted]GCTG

ligase

GCGG[redacted]

[redacted]

ligase

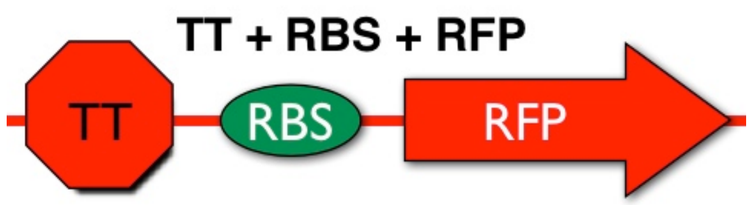
Bsa I

CGACtGAGACC(TT)GGTCTCaGCGG

GCTGaCTCTGG(TT)CCAGAGtCGCC

ligase

Bsa I ligase



CGACtGAGACC(TT)GGTCTCa

aCTCTGG(TT)CCAGAGtCGCC

[redacted]GCGG[redacted]

[redacted]GCTG

[redacted]

ligase

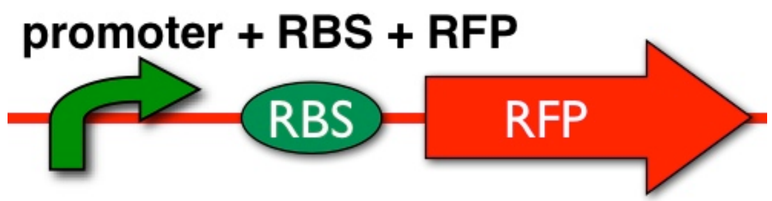
ligase

CGAC(promoter)

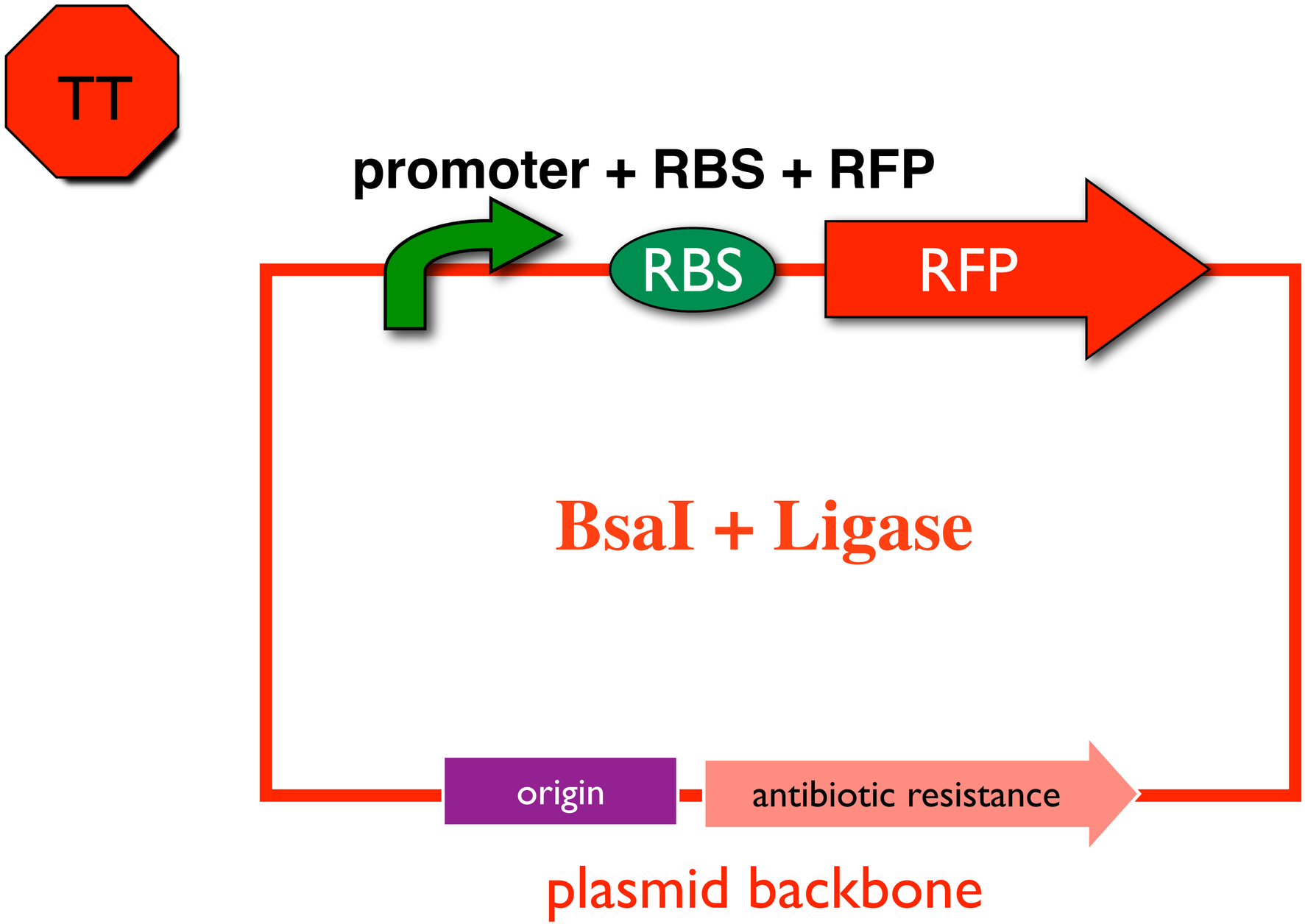
(promoter)CGCC

CGACtGAGACC(TT)GGTCTCa

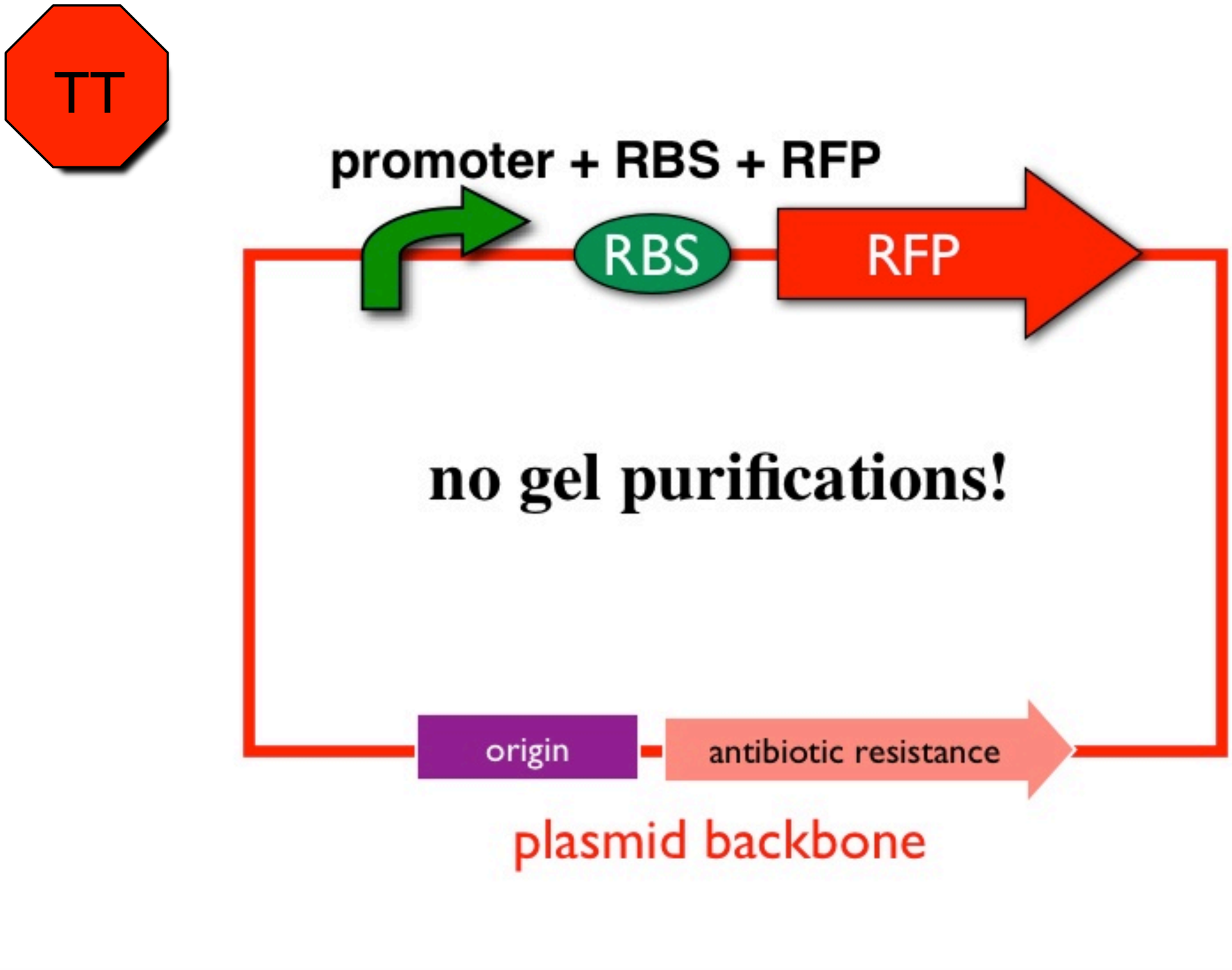
aCTCTGG(TT)CCAGAGtCGCC



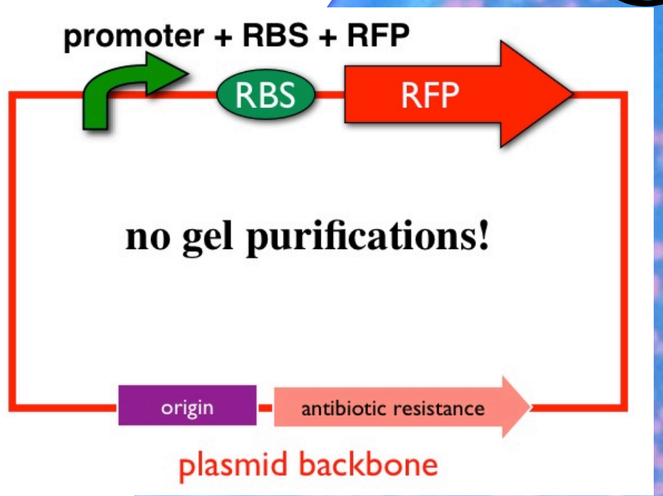
GGA Ligation Method



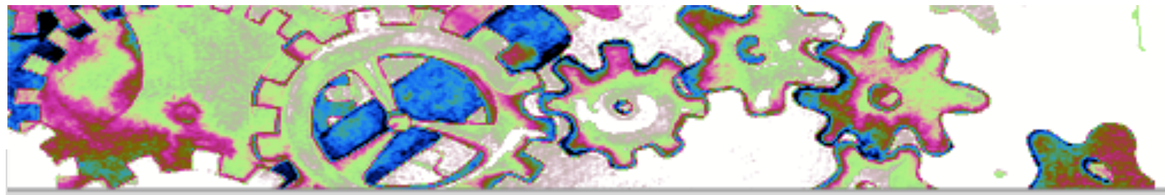
GGA Ligation Method



GGA Ligation Method



Student Sample, September 2012



Registry of Standard Biological Parts

		BBa_J100067	Regulatory	fadB promoter (long sequence)	Meredith Nakano	85
		BBa_J100068	Regulatory	fadB promoter (short sequence)	Meredith Nakano	61
		BBa_J100069	Reporter	Superfolder GFP	Rebecca Evans	770
		BBa_J100070	Coding	Superfolder GFP	Rebecca Evans	720
		BBa_J100071	Regulatory	cadA promoter	Ben Clarkson	334
		BBa_J100072	Regulatory	LcpxP promoter--Long cpxP promoter	Ben Clarkson	392
		BBa_J100073	Regulatory	ScpxP--Short cpxP promoter	Ben Clarkson	94
		BBa_J100074	Regulatory	Long pLux Promoter	Betsy Gammon	197
		BBa_J100075	Regulatory	CydAP1 Long Promoter	Betsy Gammon	158
		BBa_J100076	Regulatory	CydAP1 Short Promoter	Betsy Gammon	151
		BBa_J100077	Composite	J10068:K0903005	Meredith Nakano	793
		BBa_J100078	Composite	J100067:K0903005	Meredith Nakano	817
		BBa_J100079	Device	Riboswitch and GFP	Rebecca Evans	879
		BBa_J100080	Device	Riboswitch and GFP	Rebecca Evans	882
		BBa_J100081	Reporter	J100071+E0240	Ben Clarkson	334
		BBa_J100082	Reporter	J100072+E0240	Ben Clarkson	1276
		BBa_J100083	Composite	LuxI Long + RBS + GFP	Betsy Gammon	1081
		BBa_J100084	Composite	CydAP Long + RBS + GFP	Betsy Gammon	1042
		BBa_J100085	RNA	short CRISPR sequence with GFP target spacer	Caroline Vrana	240
		BBa_J100086	Composite	CydAP Short Promoter + RBS + GFP	Betsy Gammon	1035
		BBa_J100087	Reporter	J100073+E0240	Ben Clarkson	978
		BBa_J100088	Generator	J100071+J10063	Ben Clarkson	2965
		BBa_J100089	Generator	J100072+J10063 (LcpxP+LRE, Luciferase)	Ben Clarkson	3023
		BBa_J100090	Regulatory	CRISPR sequence with GFP and AmpR targets	Caroline Vrana	412
	W	BBa_J100092	Regulatory	Constitutive promoter for M1-162	Natalie Spach	50
	?	BBa_J100093	Regulatory	rrnB P1 promoter	Kayla McAvoy	60
	?	BBa_J100094	Regulatory	Lac promoter E. Coli	Cameron Bard	44
	?	BBa_J100095	Regulatory	malE1 Maltose induced promoter.	Pooja Potharaju	65
		BBa_J100096	Regulatory	PBAD Promoter from araE Gene	Elizabeth Brunner	27
	W	BBa_J100097	Regulatory	Anhydrotetracycline inducible promoter with BsaI sticky ends	Sarah Kim	55
		BBa_J100098	DNA	Promoter for the argF gene	Erin Nieusma	44
	W	BBa_J100099	Regulatory	A promoter (CydAB) activated by the FNR enzyme	Phoebe Parrish	64

Student Sample, September 2012

Registry of Standard Biological Parts

Go Search

page discussion view source history Log in / create account

BBa J100099 Main Page Part Design Physical DNA Hard Information Experience Tools

Part:BBa_J100099

Designed by Phoebe Parrish Group: Campbell_M_Lab (2012-09-13)

Regulatory

DNA Planning
Experience: Works
Get This Part

A promoter (CydAB) activated by the FNR enzyme

The promoter, CydAB, was found to be activated by the FNR enzyme, which is induced by the presence of (NH4)2Fe(SO4)2 and ascorbate. The oligo includes both CydAB, the FNR binding site, and the sticky ends needed for the Golden Gate Assembly method.

Sequence and Features

Format: Subparts | Ruler | **SS** | DS **Search:** **Length: 64 bp** **Context: Part only** Get selected sequence

```
     1          11         21         31         41         51         61         71         81         91
1    ggaattgata tttatcaatg tataagtctt ggaaatgggc atcaaaaaga gataaattgt tctc
```

FNR binding -35 -10

Assembly Compatibility: 10 12 21 23 25

Jeffrey Green. 1993. "Activation of FNR-dependent transcription by iron: An in vitro switch for FNR." FEMS Microbiology Letters 113 (1993) 219-222

[edit]

Student Sample, September 2012

Part:BBa_J100099:Experience

Designed by Phoebe Parrish Group: Campbell_M_Lab (2012-09-13)

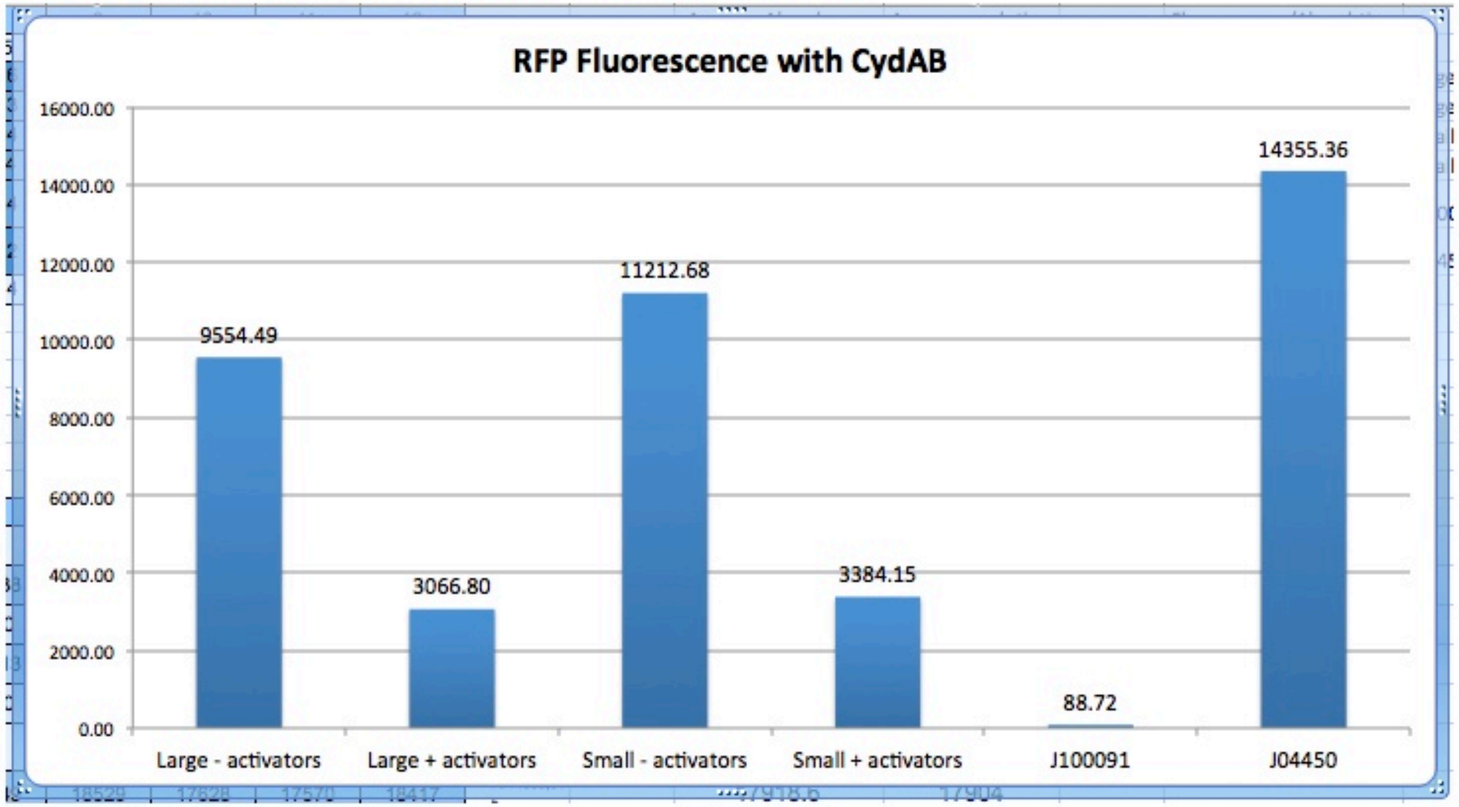
Regulatory

DNA Planning
Experience: Works
Get This Part

This experience page is provided so that any user may enter their experience using this part.
Please enter how you used this part and how it worked out.

Applications of BBa_J100099

We pipetted 200 microliters of one solution containing E coli cells from a small colony and the activators, one with cells from a small colony and no activators, one containing cells from a large colony and the activators, and one containing cells from a large colony and no activators. We also did a positive control with E coli cells containing a known promoter that causes red florescence (J04450) and a negative control with cells containing a the transcriptional terminator that does not cause red fluorescence (J100091). We tested both fluorescence of our samples using a fluorometer and the light absorbance using a spectrophotometer. We measured the fluorescence and absorbance of five samples of each solution, including a control solution that just contained the growth medium. We averaged the values for each solution and subtracted the average fluorescence/absorbance of the control. We then divided the average fluorescence by the average absorbance for each solution. These values are displayed on the accompanying graph.



Registry of Functional Promoters (RFP)

Registry of Functional Promoters (V1.0)

Welcome to the Registry of Functional Promoters

This Registry of Functional Promoters was developed by Bill Hatfield, Laurie J. Heyer, A. Malcolm Campbell at Davidson College and Todd Eckdahl of Missouri Western State University, through the support of HHMI grant 52006292 (GCA T main page) and is freely available for others to use though no support other than the user manual is available.

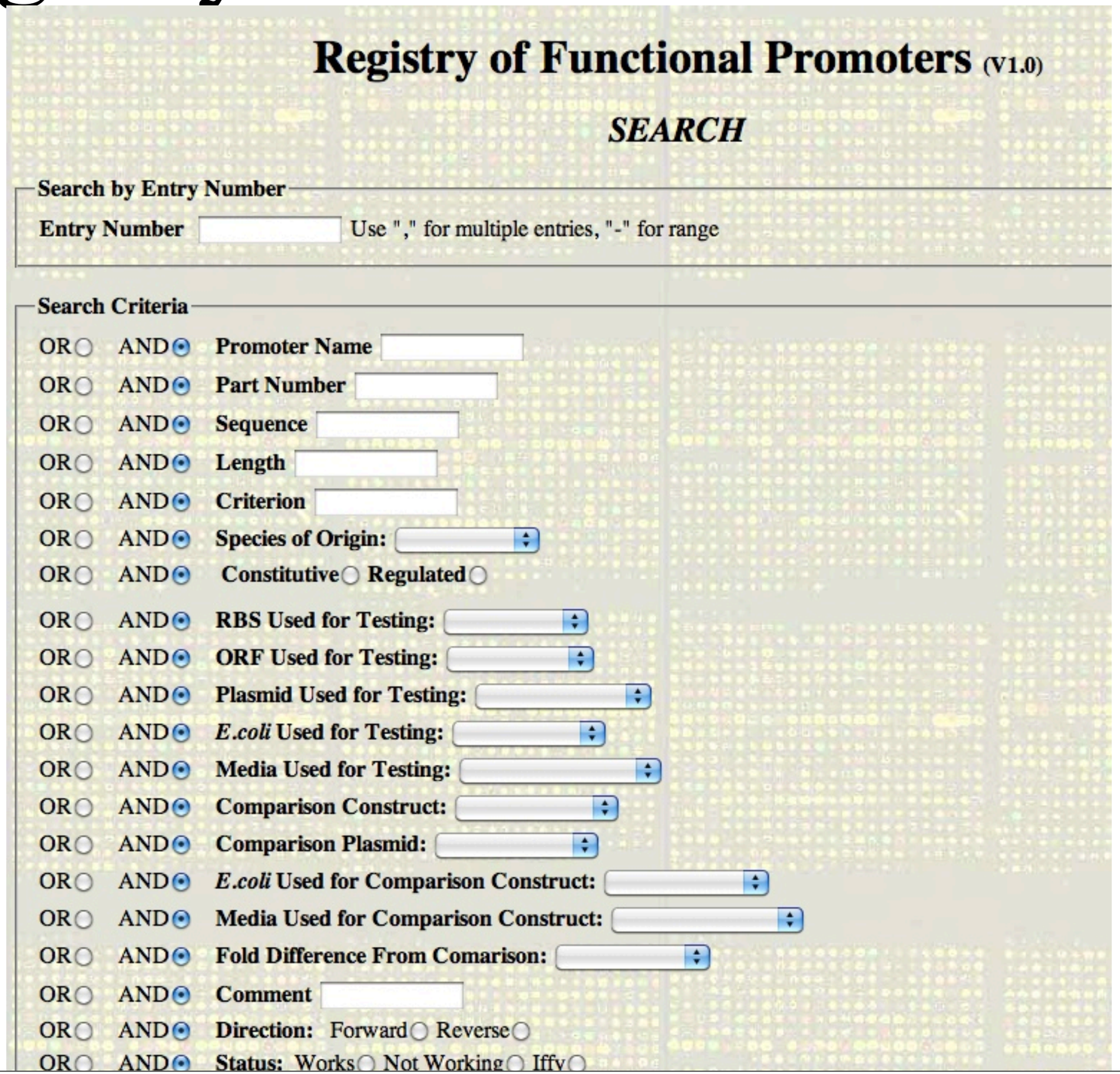
If your are already a Registered User of GCAT-alog , you do not need to Reregister

LOGIN **REGISTER AS NEW USER**

- For comments or questions about this website contact, Malcolm Campbell

gcat.davidson.edu/RFP/

Registry of Functional Promoters (RFP)



Registry of Functional Promoters (V1.0)

SEARCH

Search by Entry Number

Entry Number Use "," for multiple entries, "-" for range

Search Criteria

OR AND **Promoter Name**
OR AND **Part Number**
OR AND **Sequence**
OR AND **Length**
OR AND **Criterion**
OR AND **Species of Origin:**
OR AND **Constitutive** **Regulated**
OR AND **RBS Used for Testing:**
OR AND **ORF Used for Testing:**
OR AND **Plasmid Used for Testing:**
OR AND ***E.coli* Used for Testing:**
OR AND **Media Used for Testing:**
OR AND **Comparison Construct:**
OR AND **Comparison Plasmid:**
OR AND ***E.coli* Used for Comparison Construct:**
OR AND **Media Used for Comparison Construct:**
OR AND **Fold Difference From Comarison:**
OR AND **Comment**
OR AND **Direction:** Forward Reverse
OR AND **Status:** Works Not Working Iffy

gcat.davidson.edu/RFP/

Registry of Functional Promoters (RFP)

Registry of Functional Promoters (V1.0)

SEARCH PROMOTER RESULTS

Entry No.	Promoter Name	Part Number	Sequence	Length	Citation	Species of Interest	Constitutive/ Regulated	Inducible/ Repressible	Regulator	RBS Used for Testing	ORF Used for Testing	Pla Use Te
1	TetR Repressible Promoter	R0040	tccctatcagtgatagagattgacatccctatcagtgatagagatactgagcac	54			Regulated	Repressible	TetR			pSE
2	56 bp LacI Promoter	K091110	cgttgacaccatcgaatggcgcaaaacctttcgcggtatggcatgatagcgcccgg	56			Constitutive					
3	200 bp LacI Promoter	R0010	caatacgcaaaccgcctctccccgcgcgttggccgattcattaatgcagctggcac gacaggtttcccgactggaaagcgggcagtgagcgcaacgcaattaatgtgagtt agctcactcattaggcaccccaggctttacactttatgcttccggctcgtatgttgtgt ggaattgtgagcggataacaatttcacaca	200			Constitutive					
4	LuxR & HSL Regulated Lux promoter	R0062	acctgtaggatcgtacaggtttacgcaagaaaatggtttgttatagtcgaataaa	55			Regulated	Repressible				
5	Backwards 200 LacI Promoter (right to left)	J31013	tgtgtgaaattgttatccgctcacaattccacacaacatacgagccggaagcataaa gtgtaaagcctggggtgcctaatgagtgagctaactcacattaattgcgttgcgctc actgcccgctttccagtcgggaaacctgtcgtgccagctgcattaatgaatcggcca acgcgcggggagaggcggtttgcgtattg	200			Regulated	Repressible				
6	OmpC Promoter	K199017	tttacattttgaaacatctatagcgataaatgaaacatcttaaaagttttagtatcatattc gtgttggattattctgcatttttggggagaatggact	99			Constitutive					
7	23K series very strong constitutive Promoter	J23100	ttgacggctagctcagtcctaggtacagtgctagc	35			Constitutive					

To Edit an Entry, Enter the Entry # and press "Edit Entry" [ ] Edit Entry

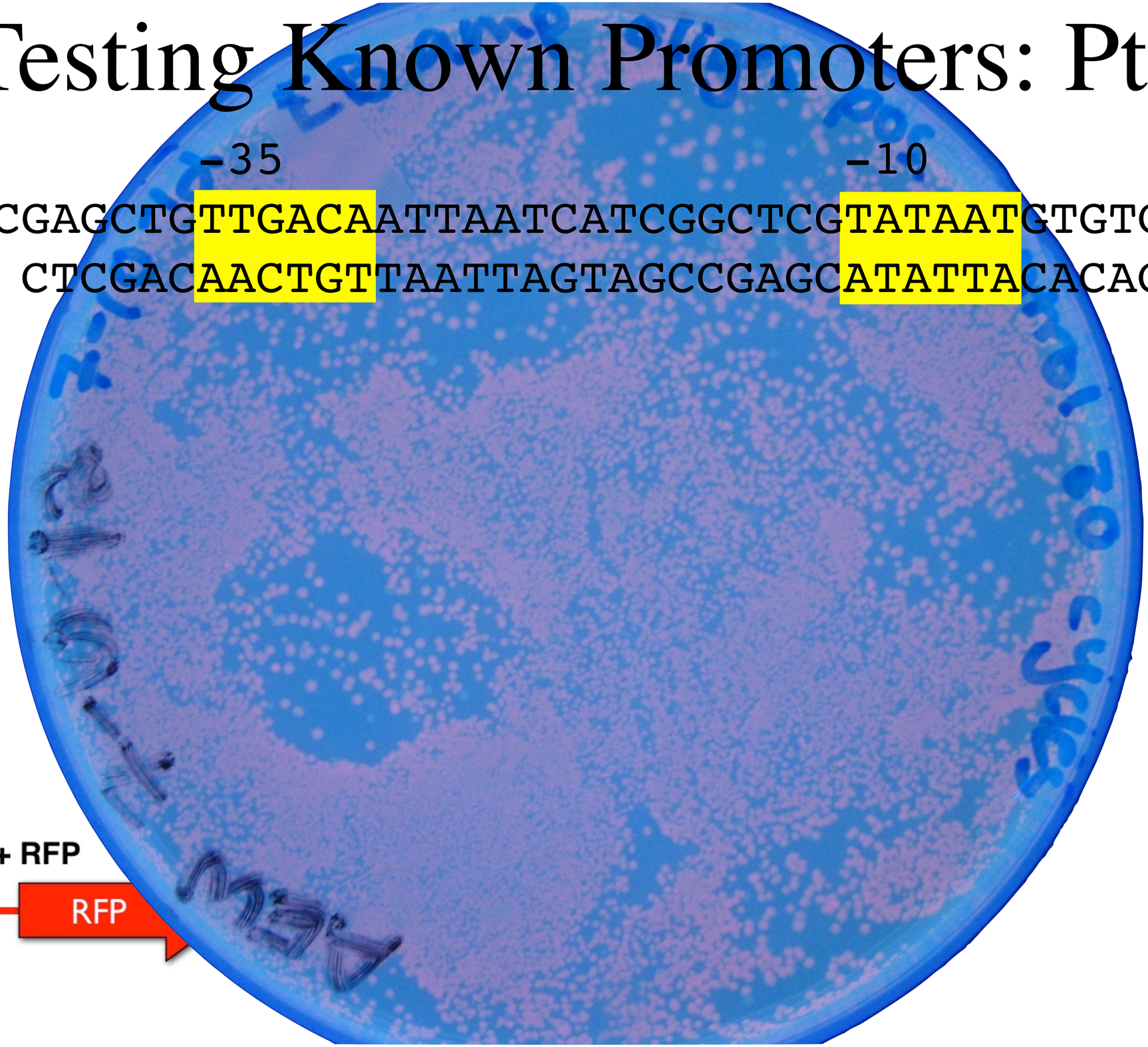
To Delete an Entry, Enter the Entry # and press "Delete Entry" [ ] Delete Entry

Search Again

gcat.davidson.edu/RFP/

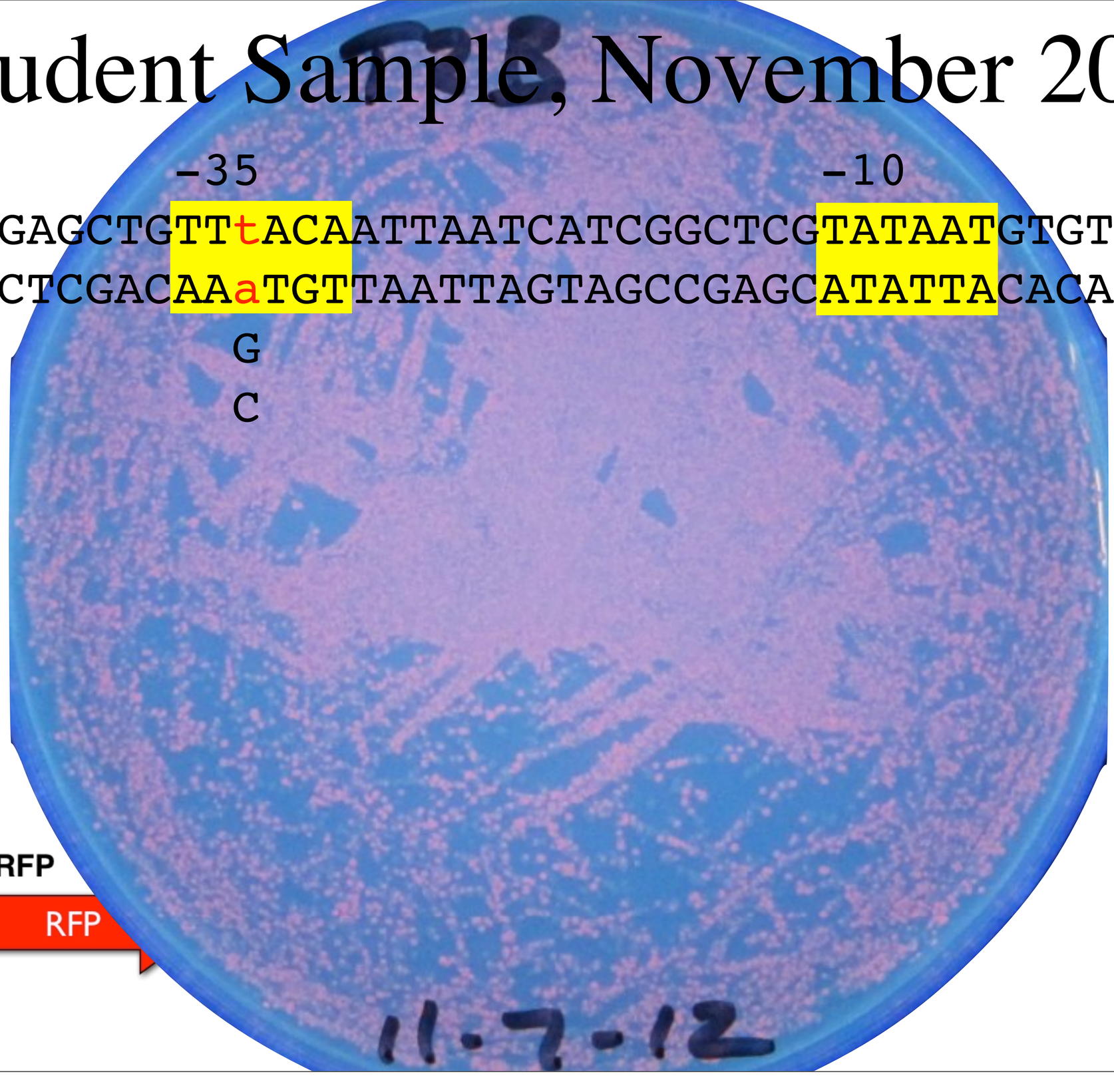
Testing Known Promoters: Ptac

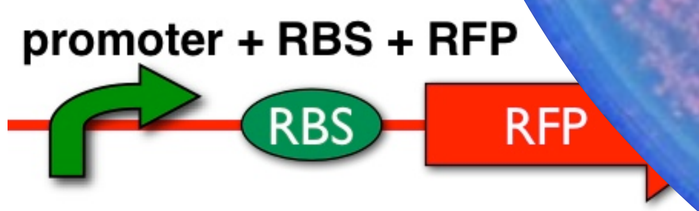
```
          -35                    -10
5′ CGACGAGCTGTTGACAATTAATCATCGGCTCGTATAATGTGTGGA      3′
3′      CTCGACAACTGTTAATTAGTAGCCGAGCATATTACACACCTCGCC 5′
```



Student Sample, November 2012

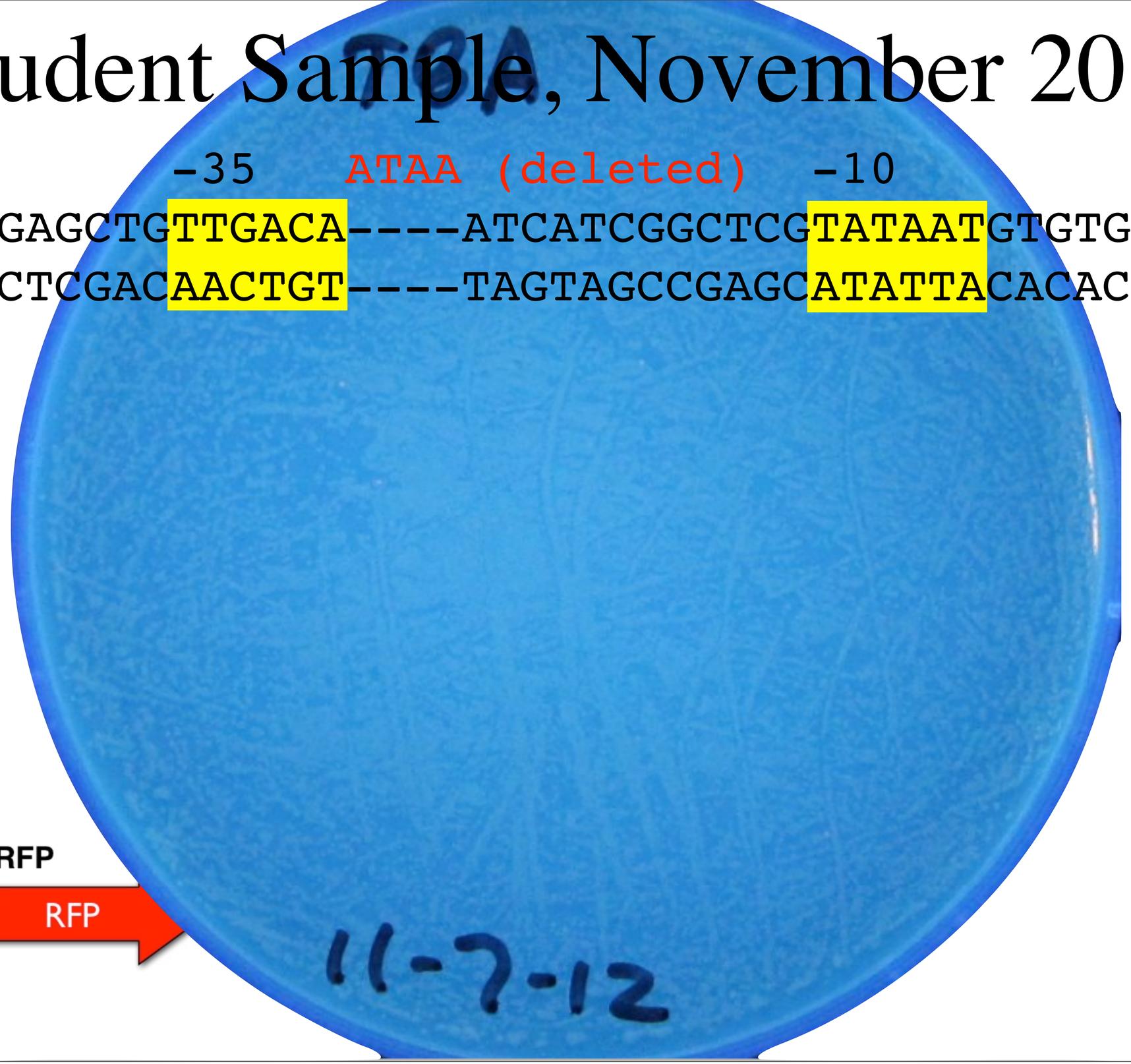
```
                  -35                          -10
5′ CGACGAGCTGTTtACAATTAATCATCGGCTCGTATAATGTGTGGA      3′
3′      CTCGACAAaTGTTAATTAGTAGCCGAGCATATTACACACCTCGCC 5′
                 G
                 C
```

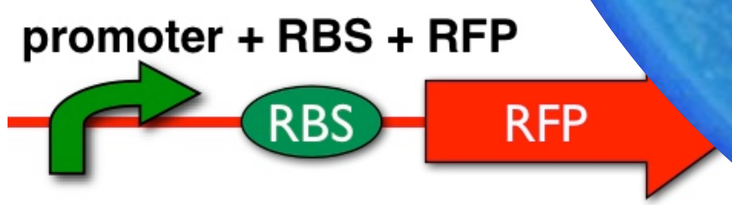




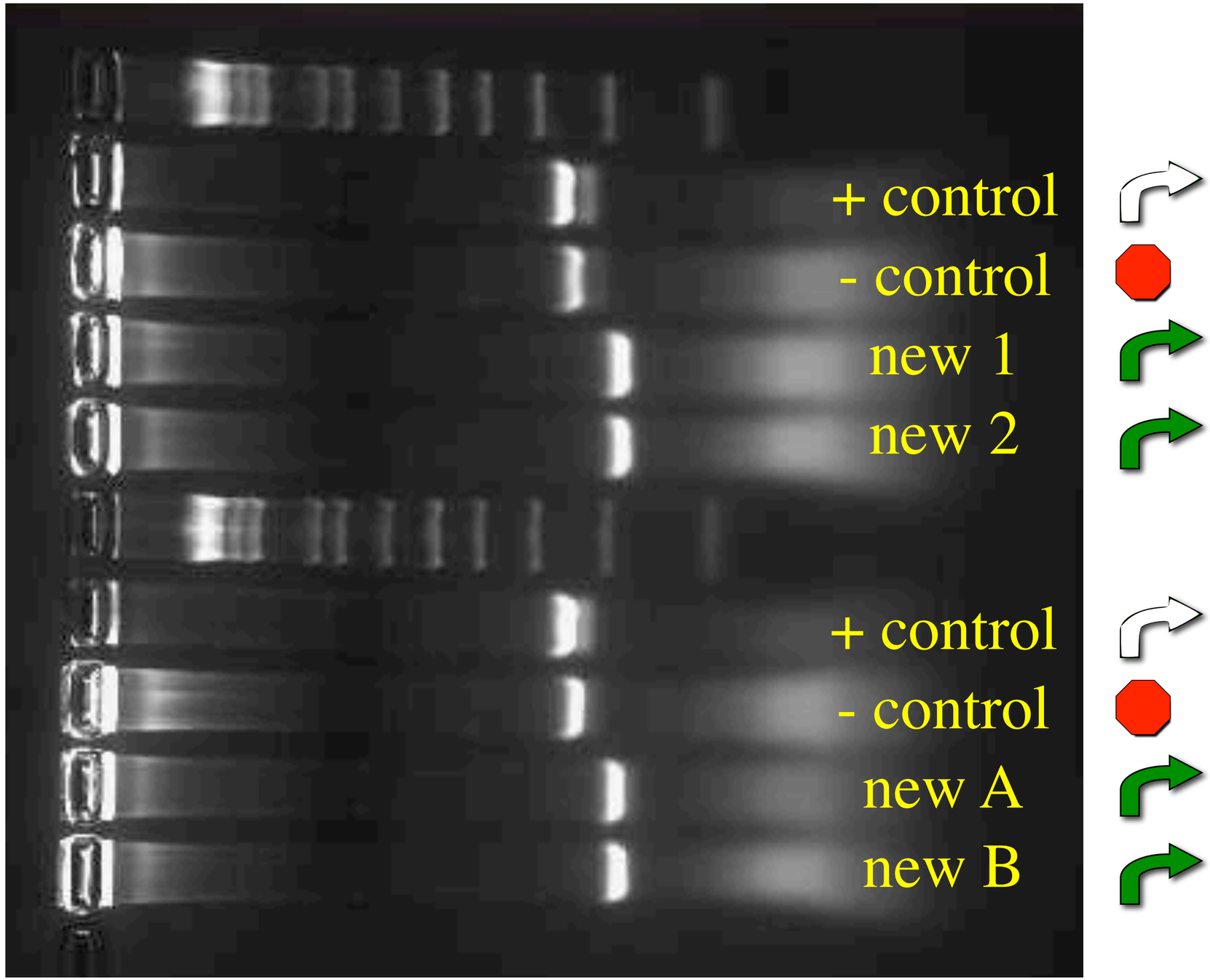
Student Sample, November 2012

```
                -35    ATAA (deleted)   -10
5′ CGACGAGCTGTTGACA----ATCATCGGCTCGTATAATGTGTGGA      3′
3′      CTCGACAACTGT----TAGTAGCCGAGCATATTACACACCTCGCC 5′
```



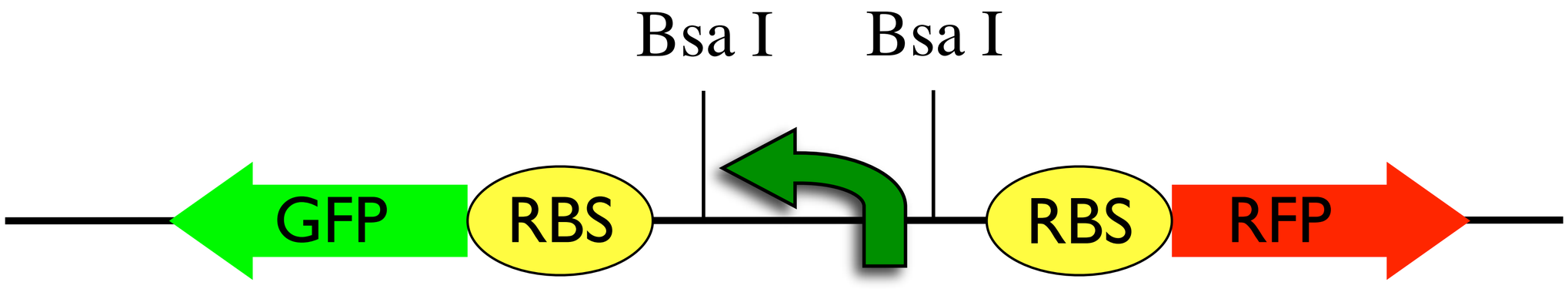


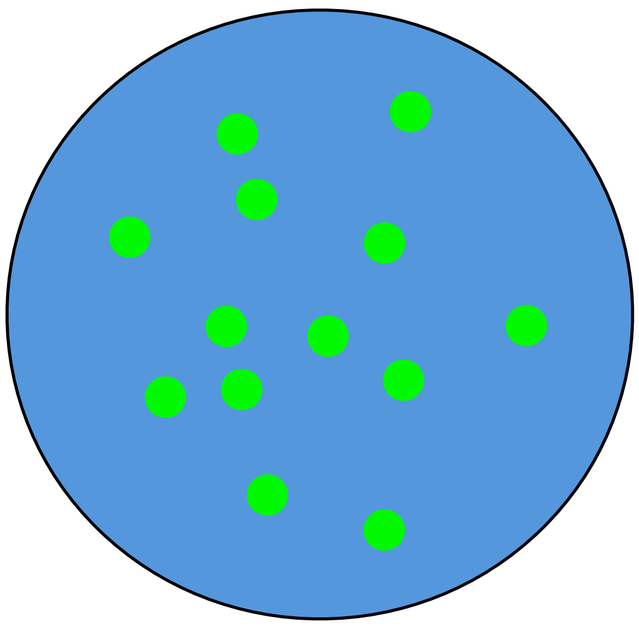
Student Sample, September 2012



pClone Red

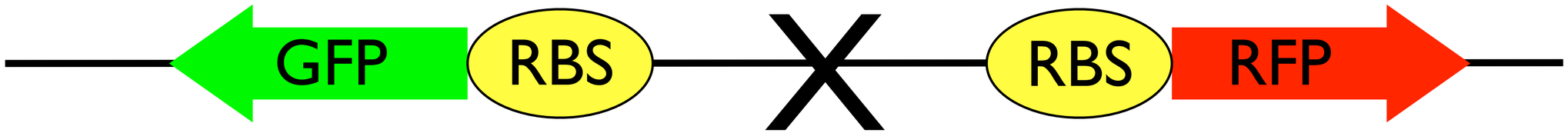
J119137

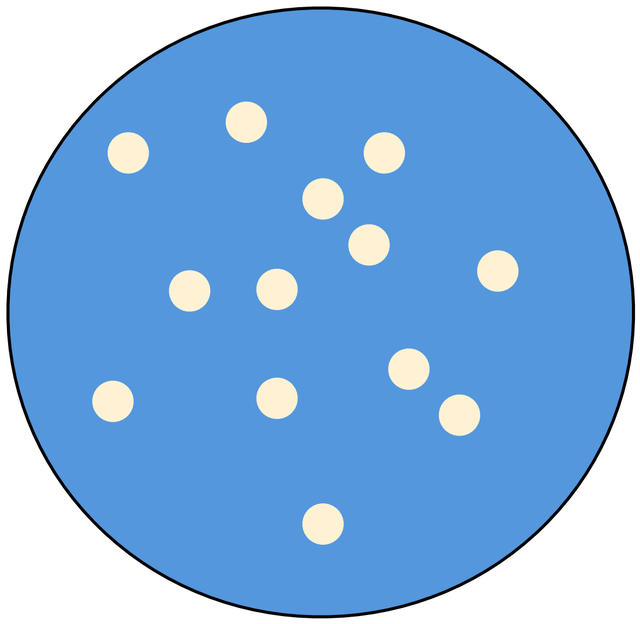




Remove Initial Promoter

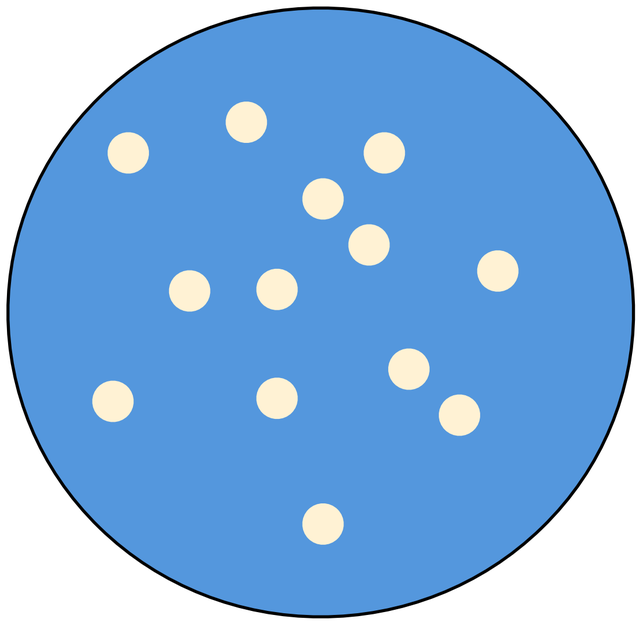
J119137





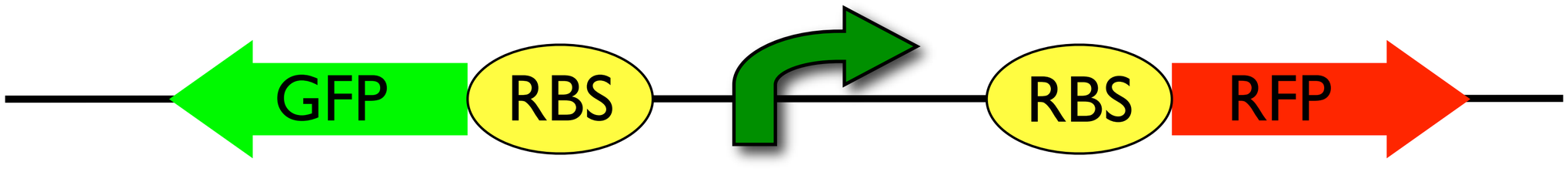
Insert Non-functional Promoter

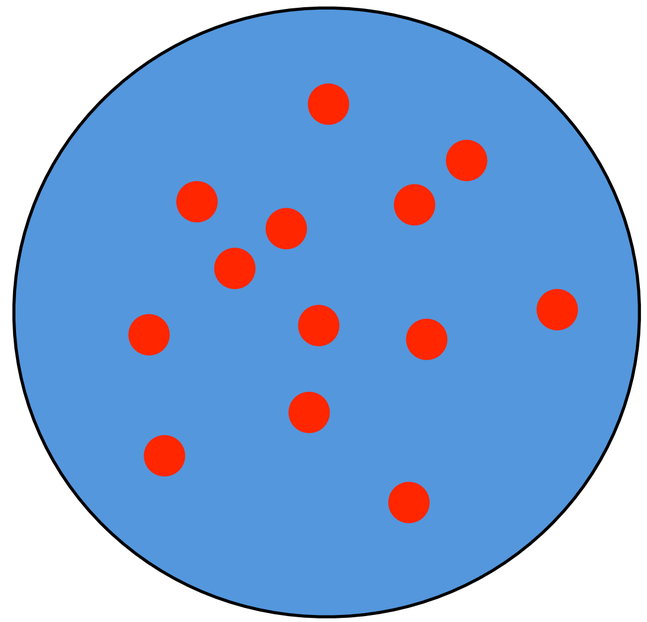
J119137



Insert Forward Promoter

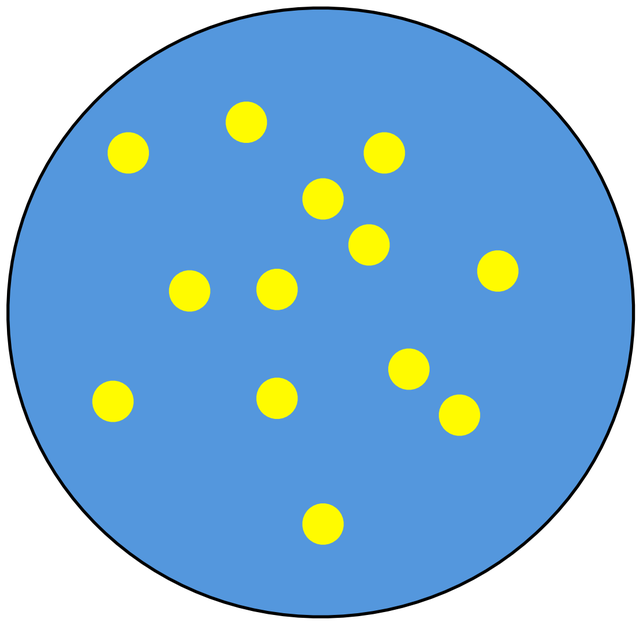
J119137





Insert Bi-directional Promoter

J119137



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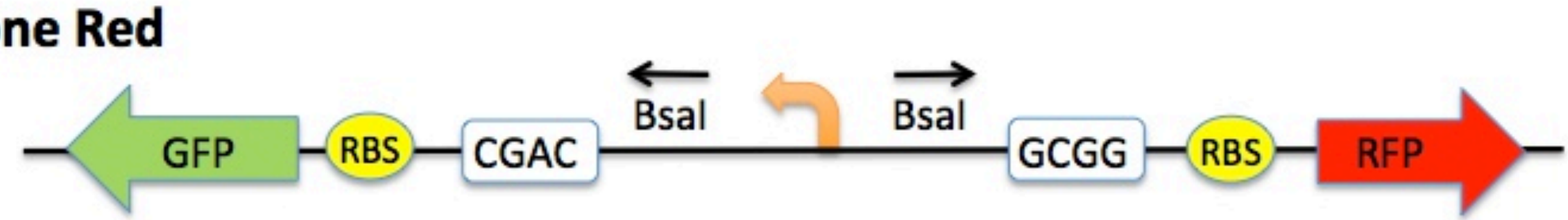
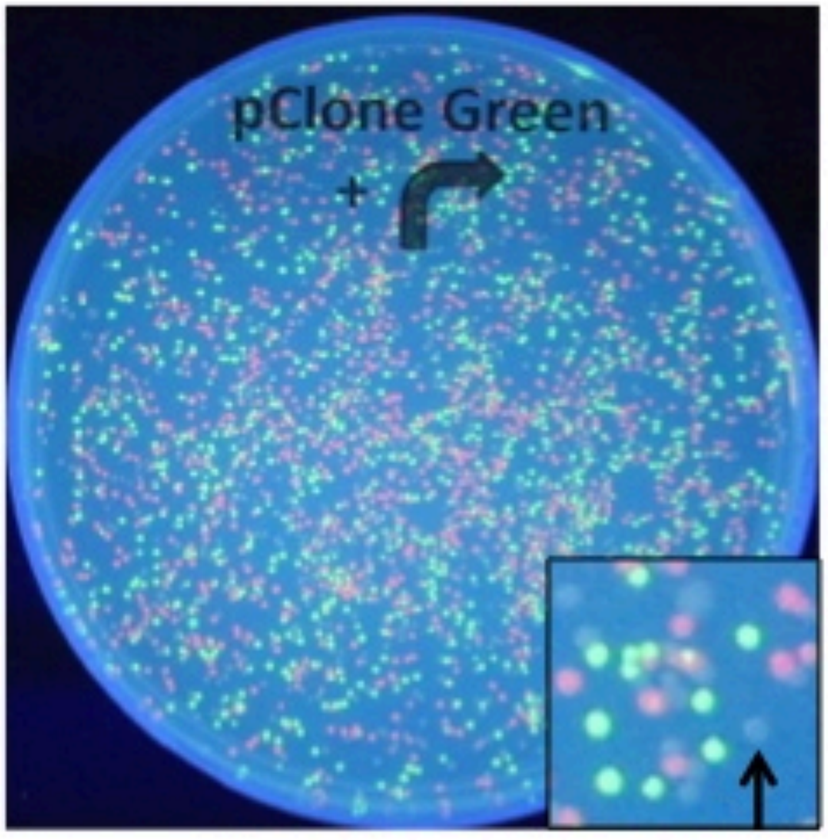
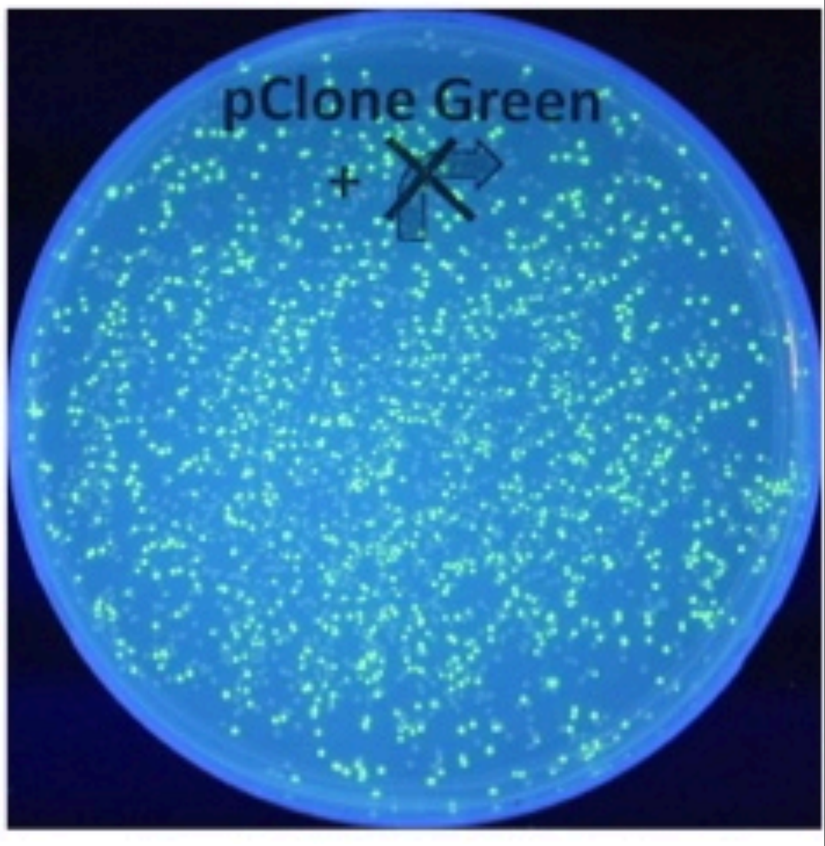


B

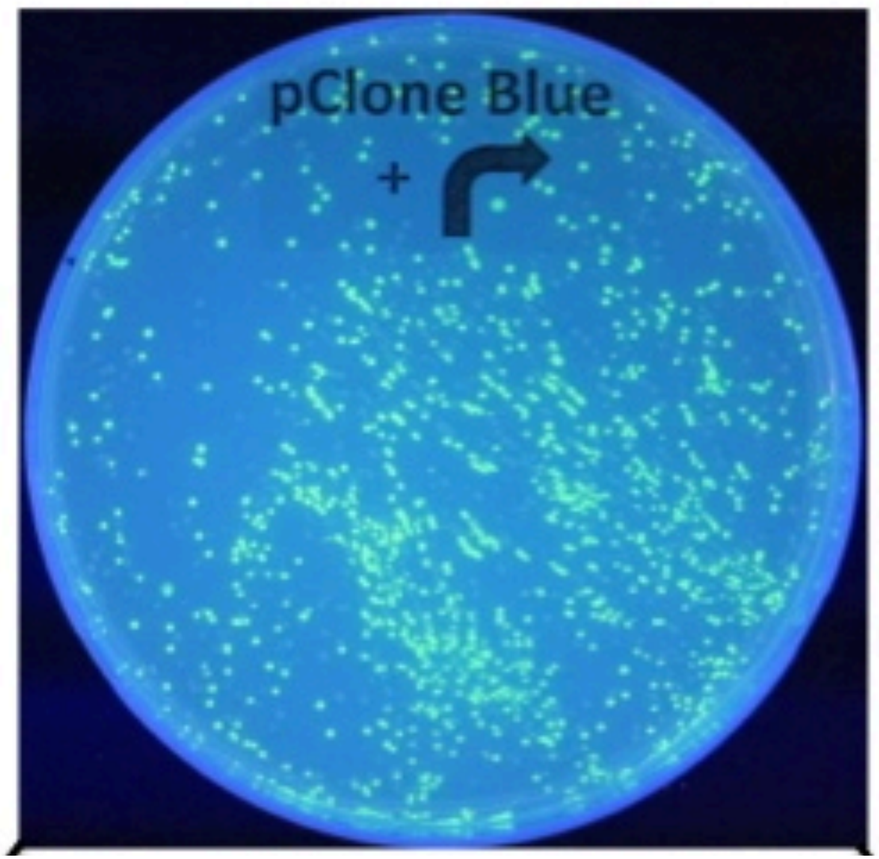


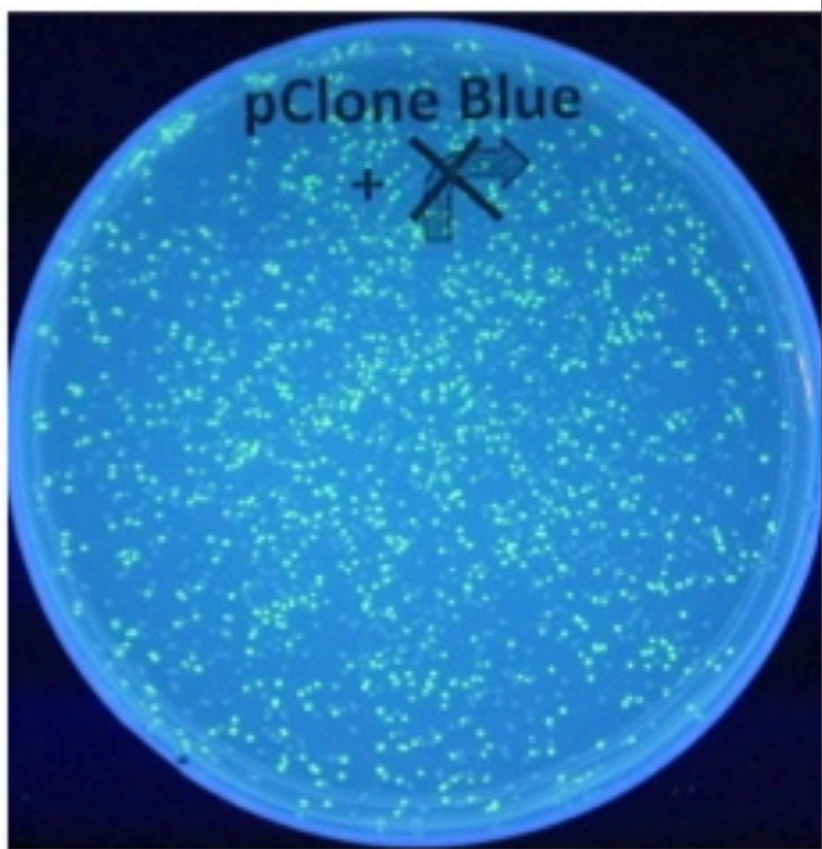


pClone Blue

A

B



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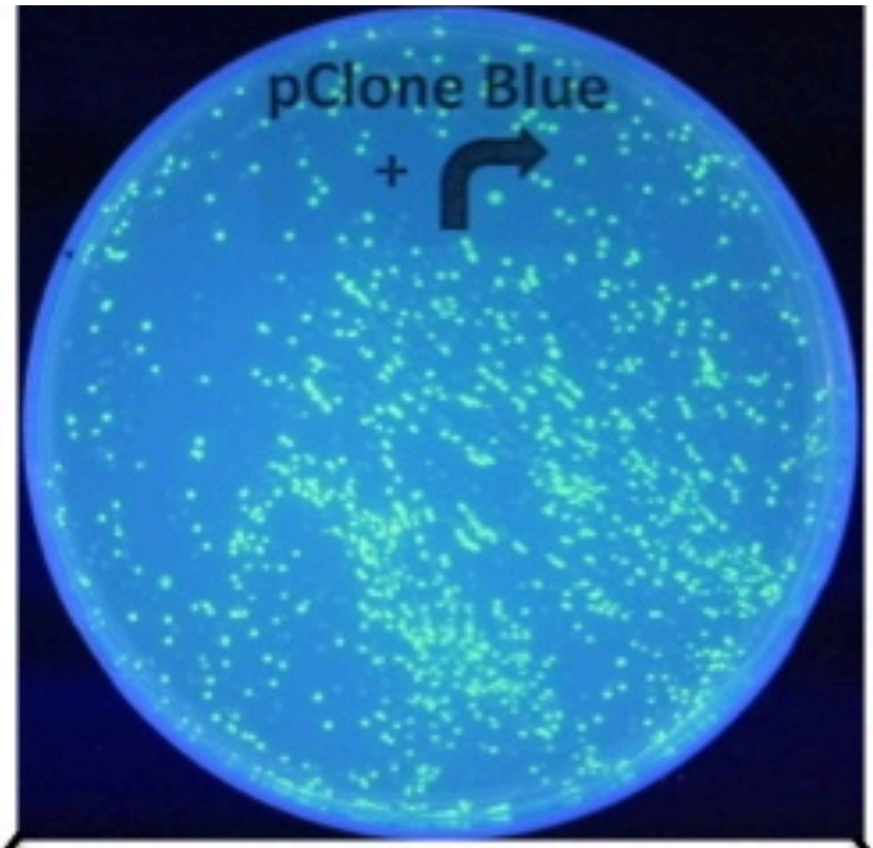
Only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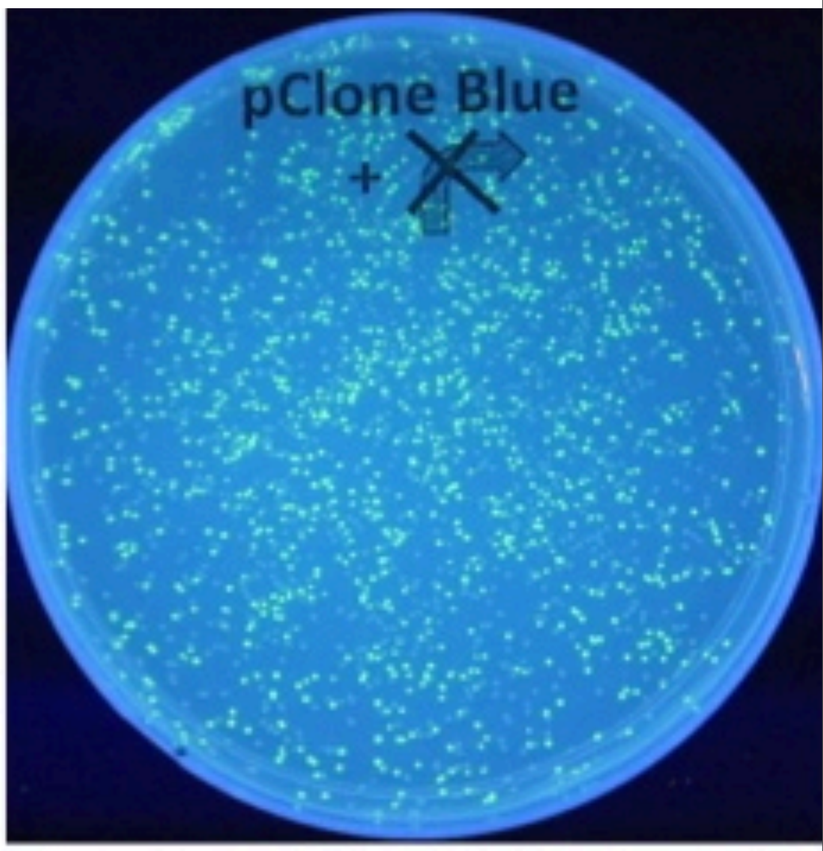
+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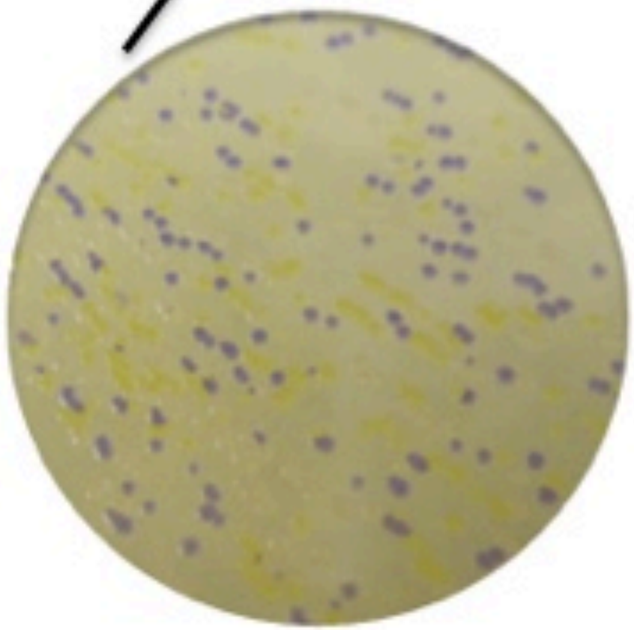

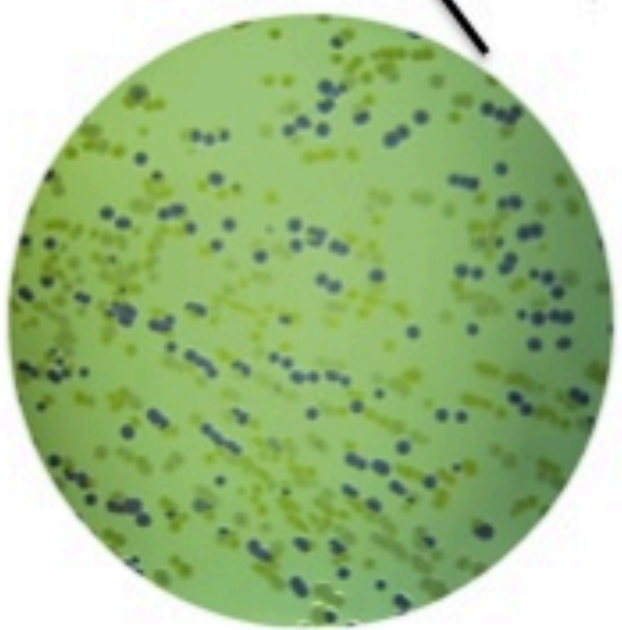

Modular Programmed Evolution of *E.coli* for Optimization of Metabolic Pathways

(research in progress)

DAVIDSON

MISSOURI WESTERN STATE UNIVERSITY

Without basic research, there can be no applications....

After all, electricity and the lightbulb were not invented by incremental improvements to the candle.

former French President Nicholas Sarkozy

Collaborative 2012 Research Team

DAVIDSON

Discover Gold WESTERN

Collaborative 2013 Research Team

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Three Rules for Student Research

1. Everyone must learn.

Three Rules for Student Research

1. Everyone must learn.
2. Everyone must have fun.

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2. Everyone must have fun.
3. We try to contribute to science.

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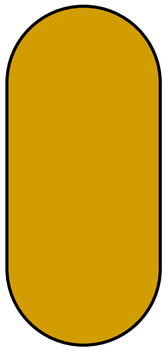
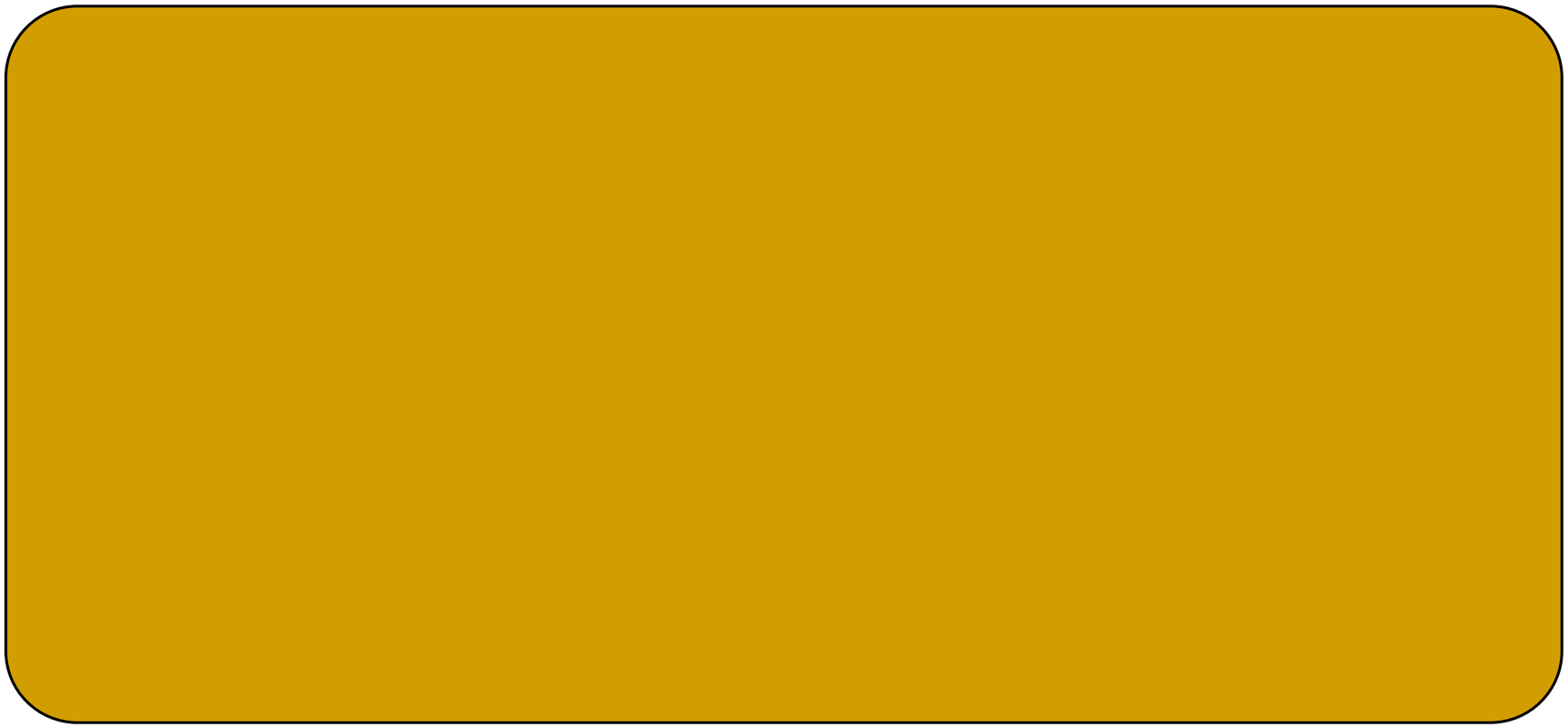


Make *E. coli* Optimize Drug Production



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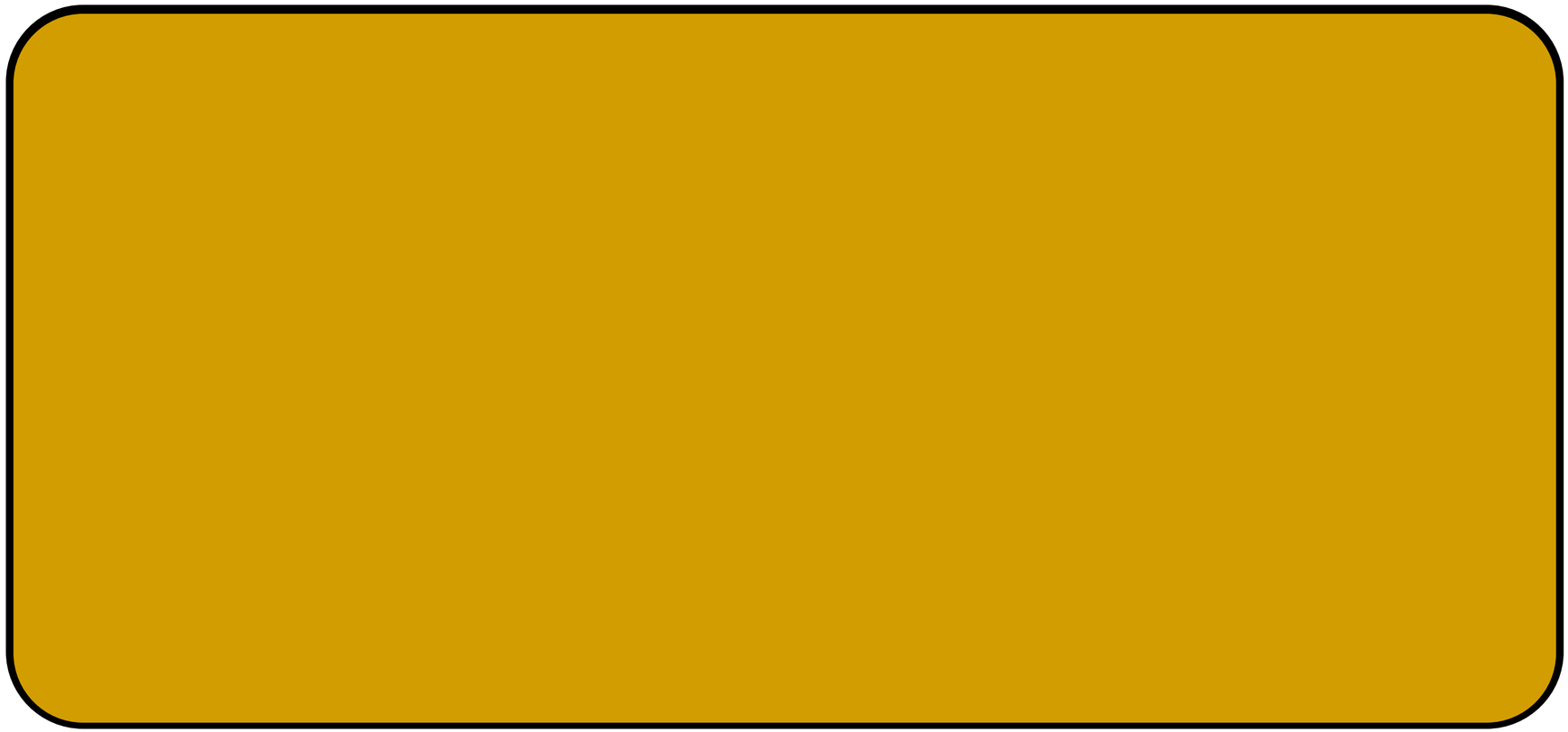
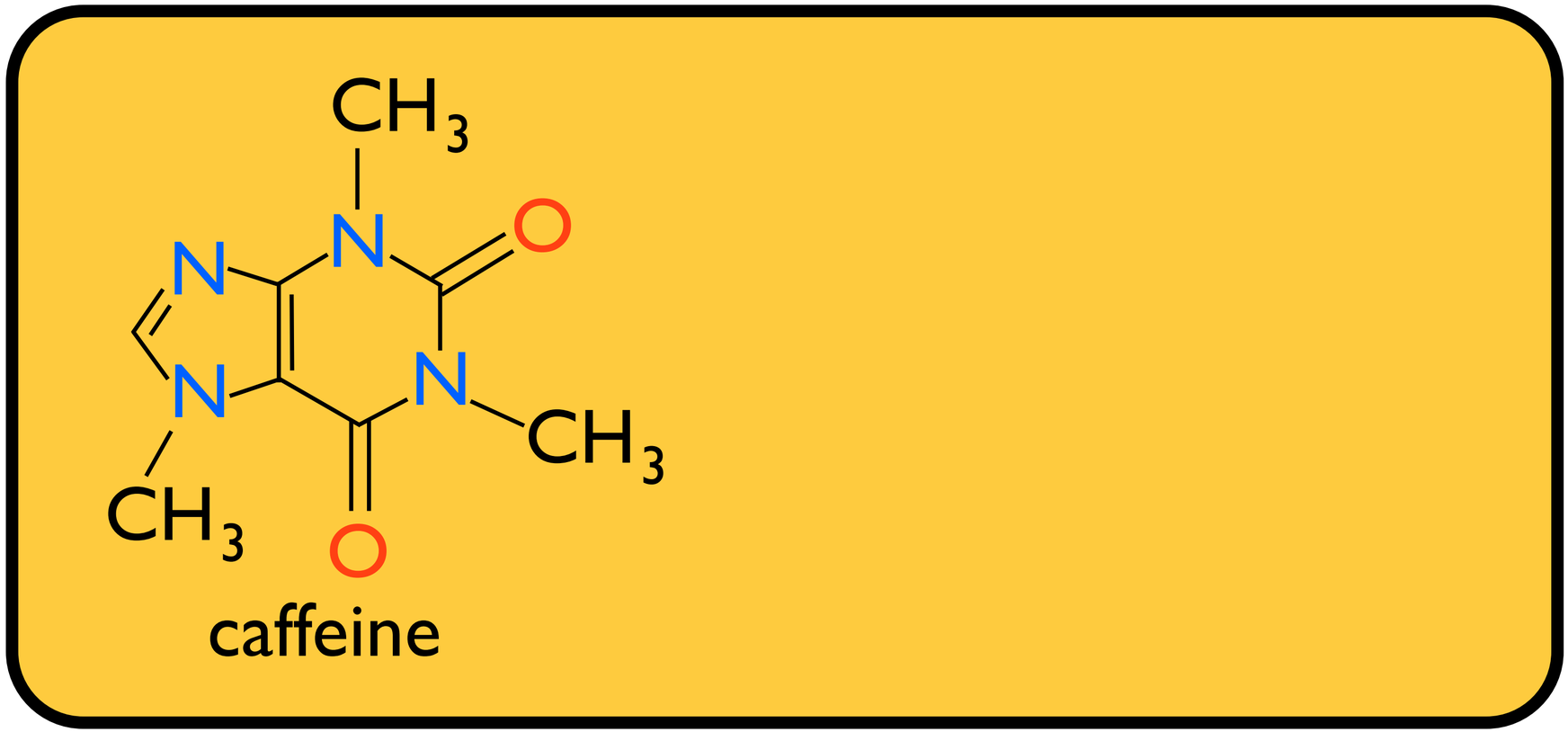
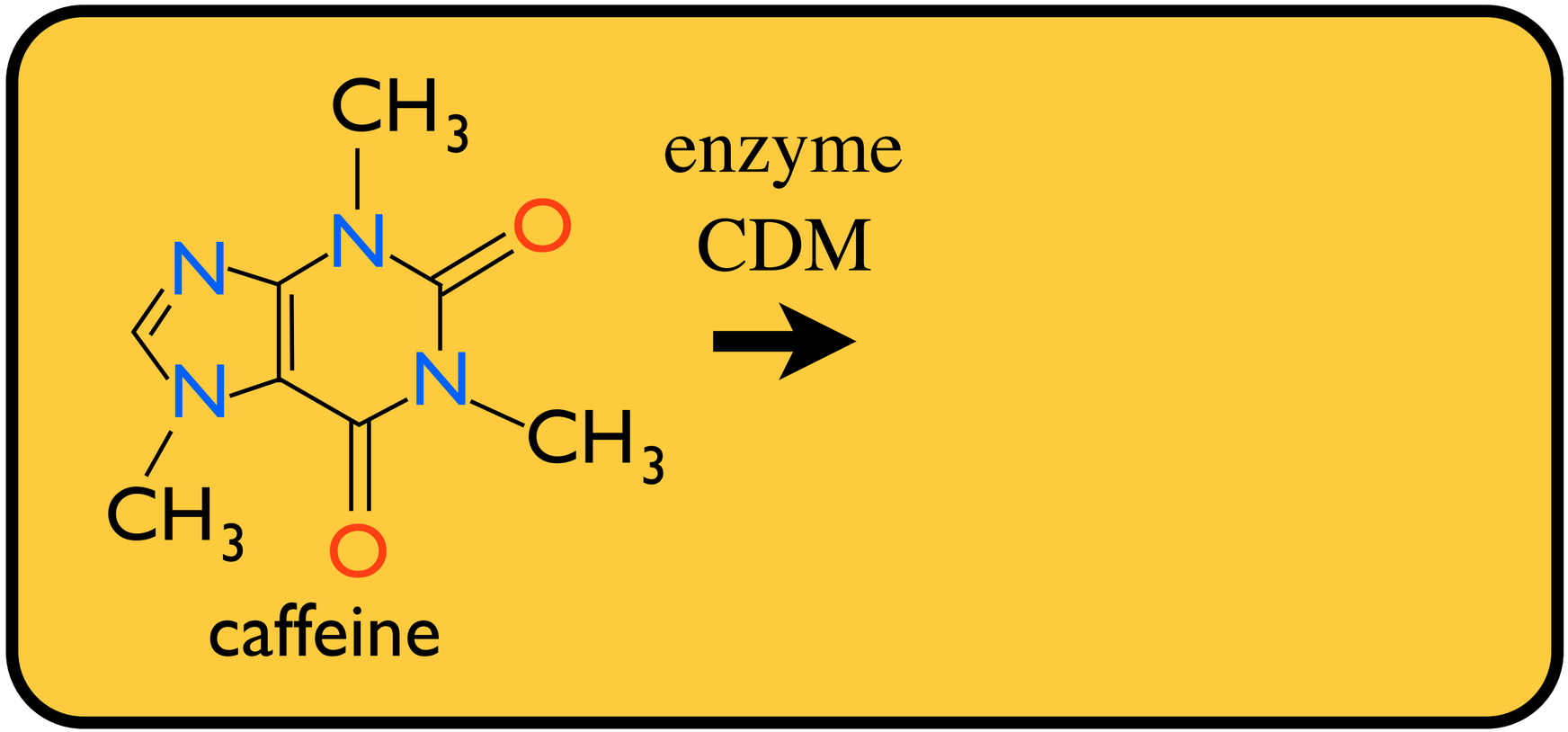


Make *E. coli* Optimize Drug Production

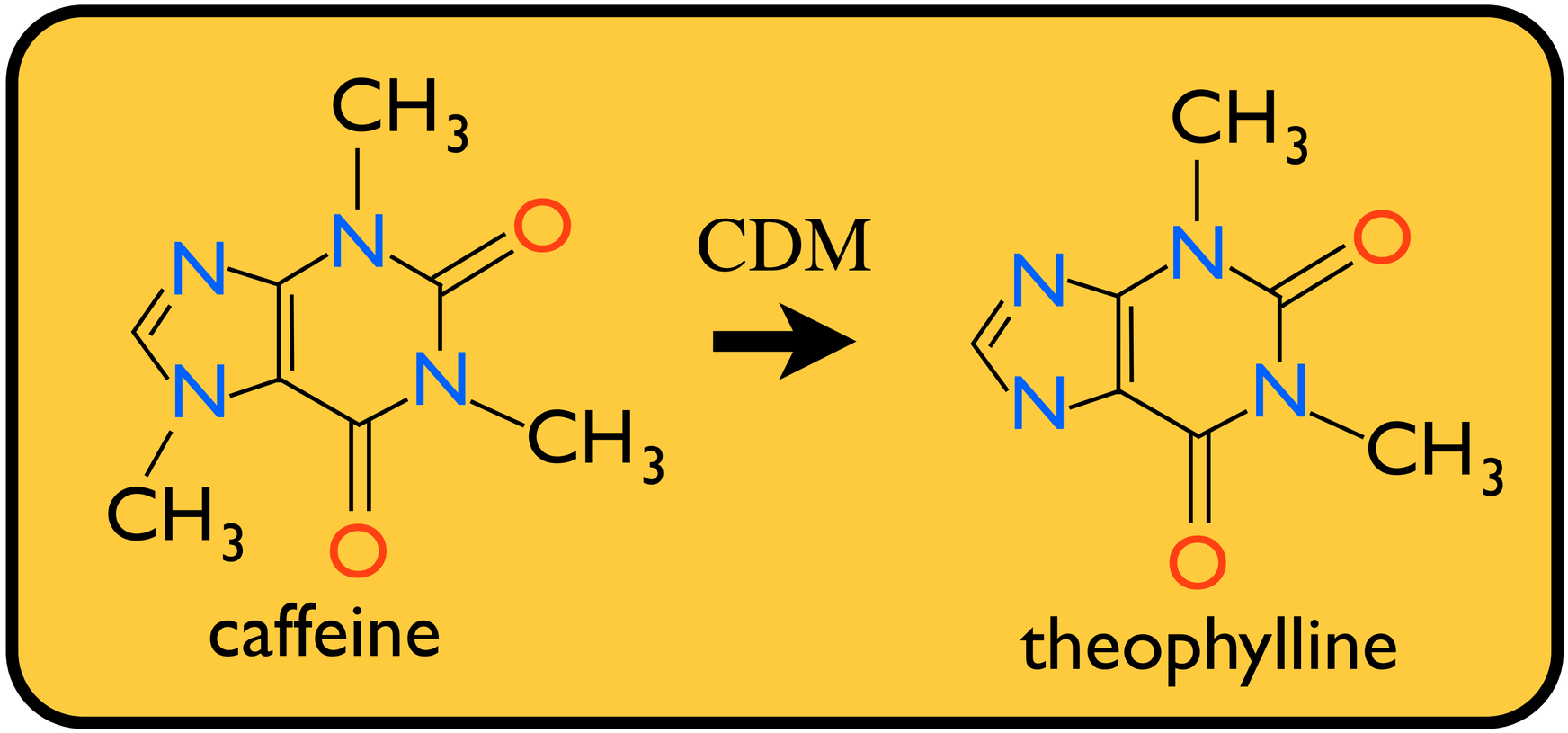


caffeine

Make *E. coli* Optimize Drug Production

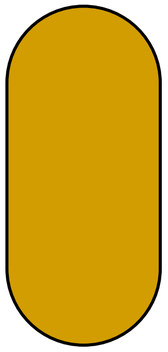


Make *E. coli* Optimize Drug Production

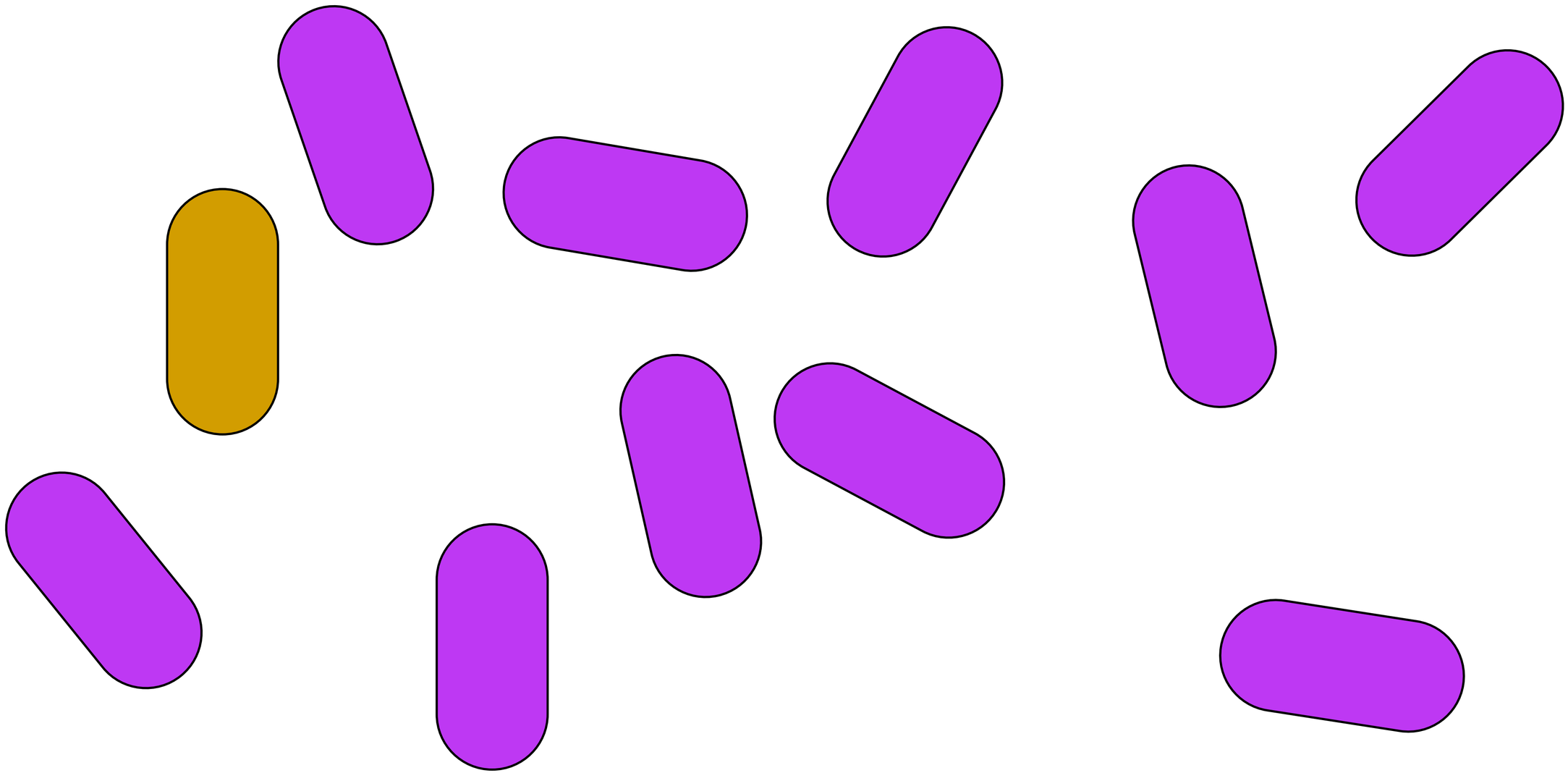


asthma medication

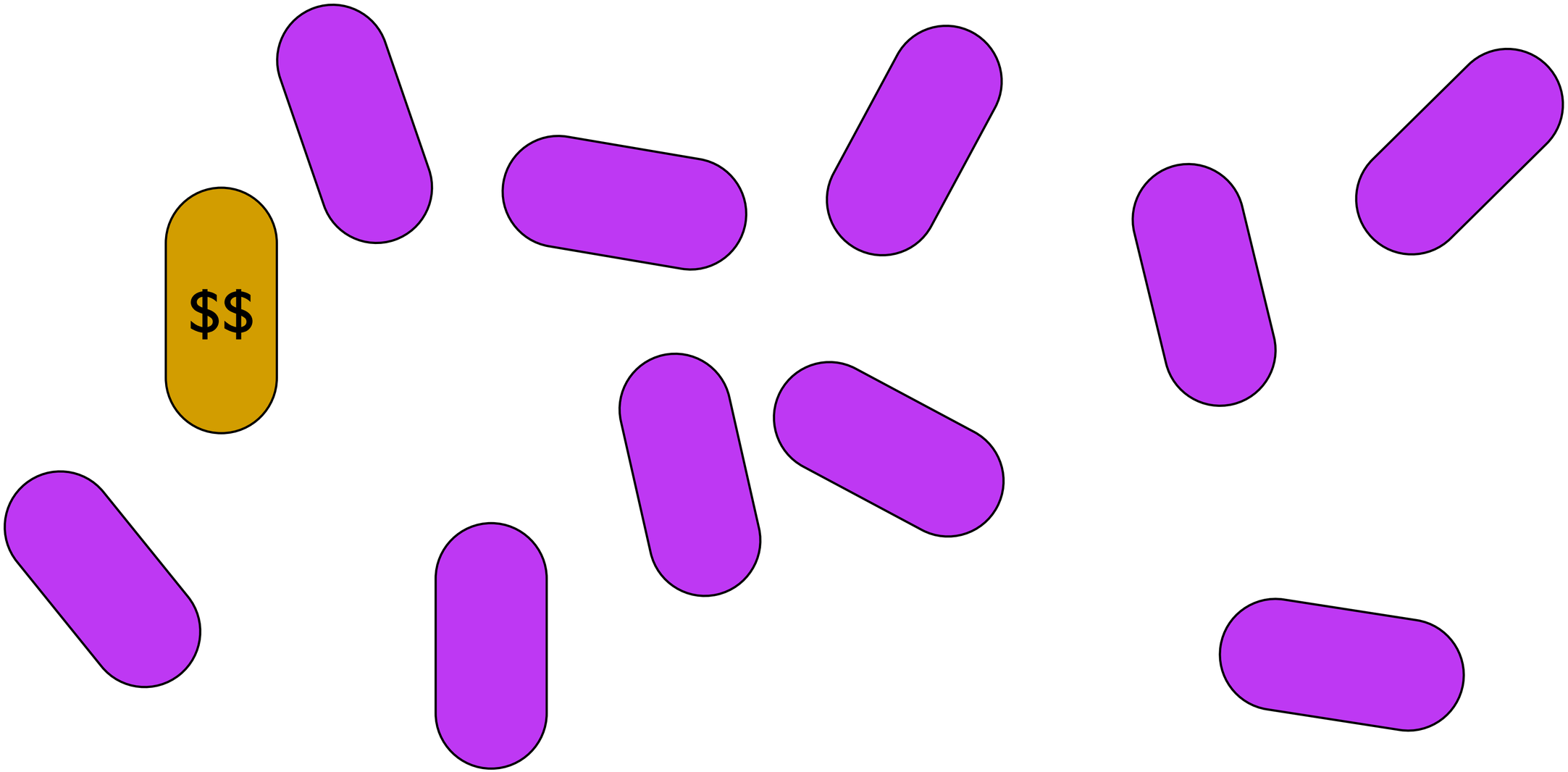
What Makes Optimization Difficult?



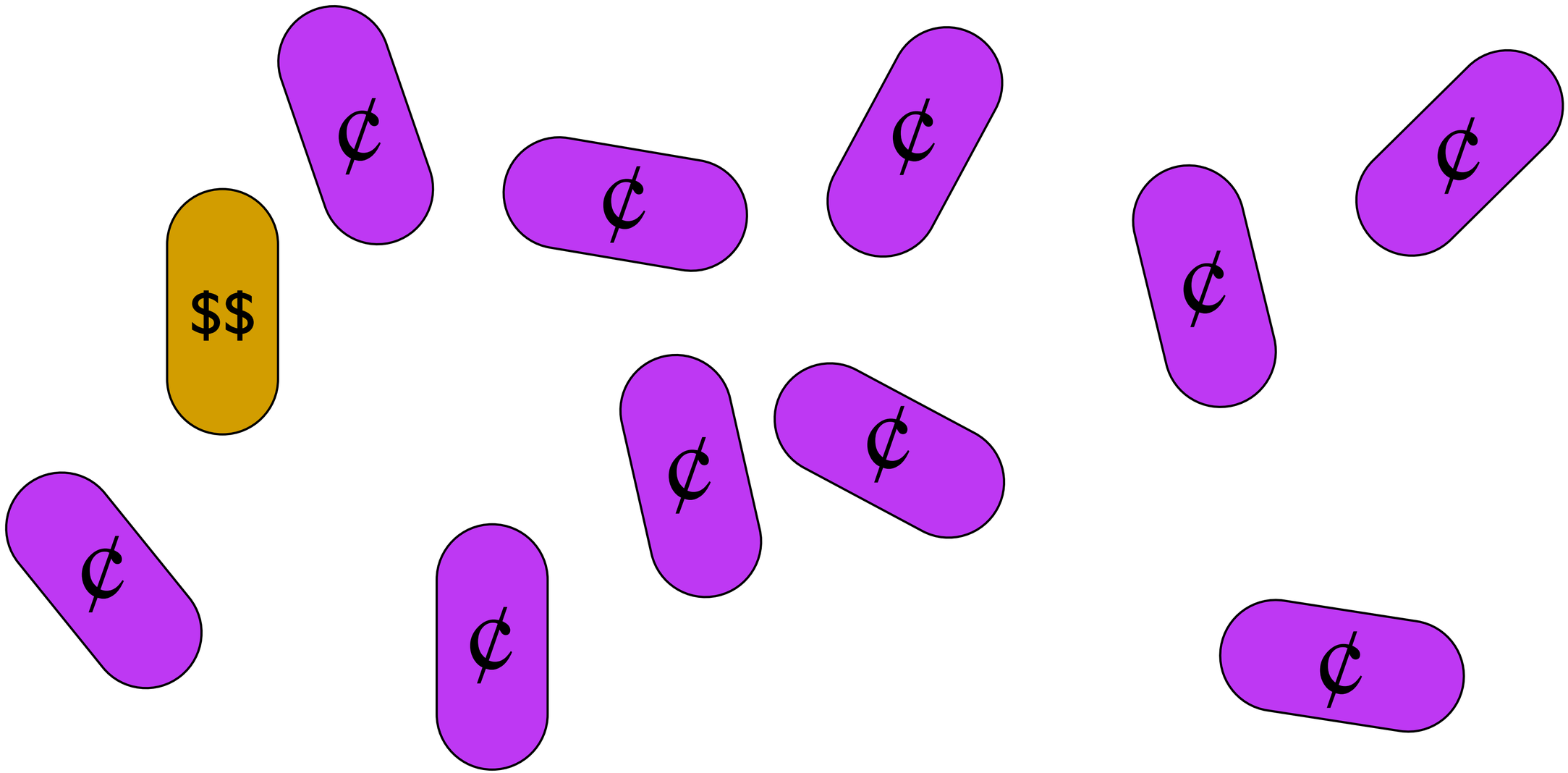
What Makes Optimization Difficult?



What Makes Optimization Difficult?



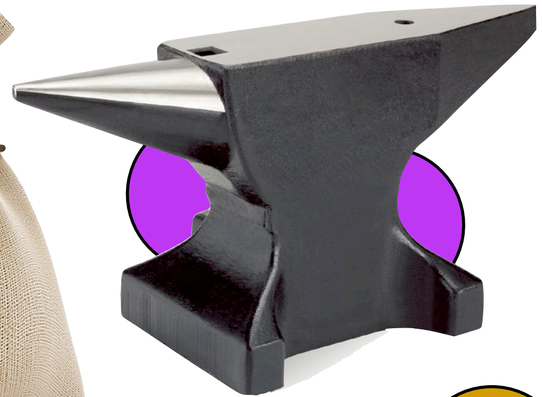
Natural Selection



Synthetic Selection

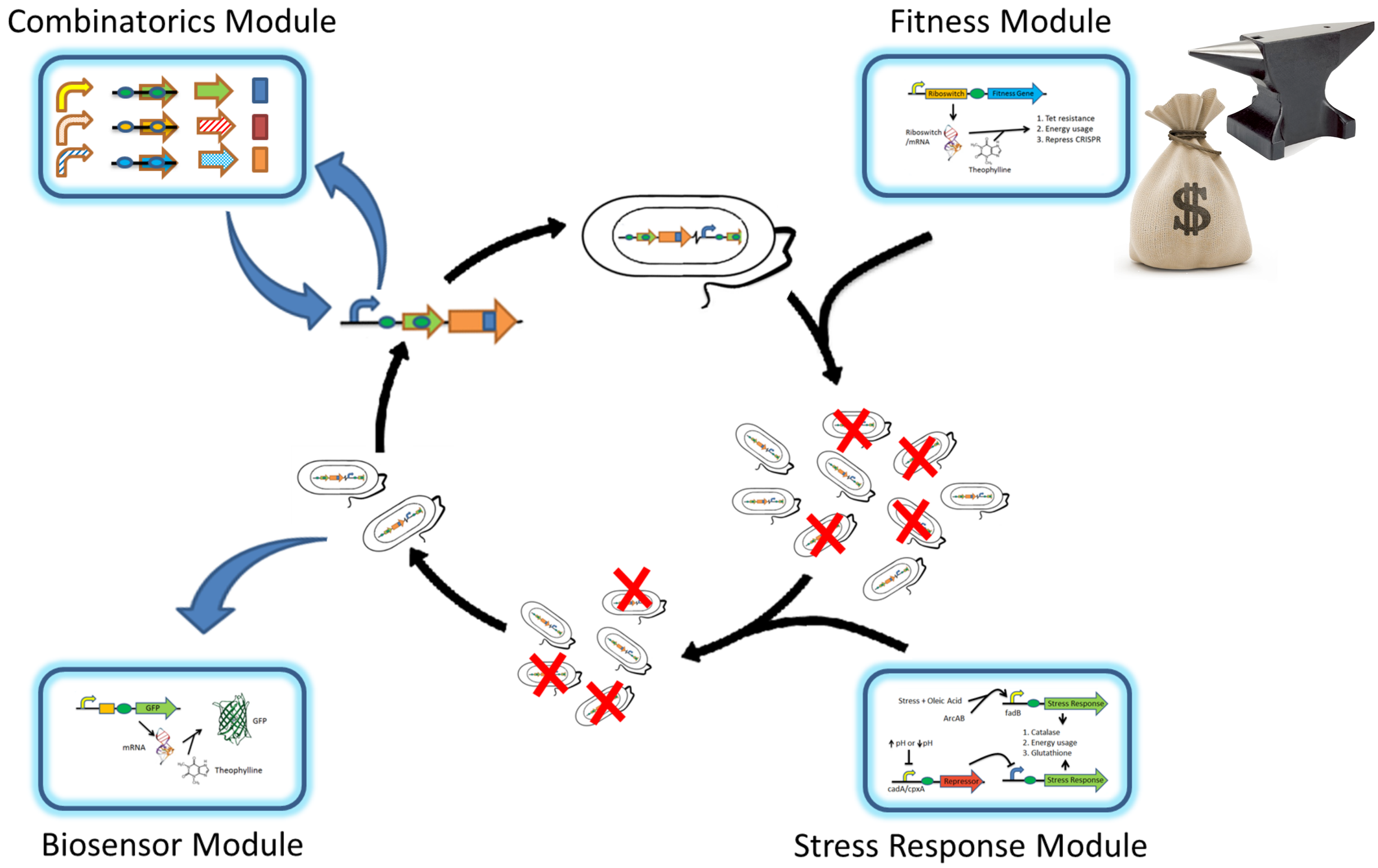
Synthetic Fitness

Synthetic Fitness

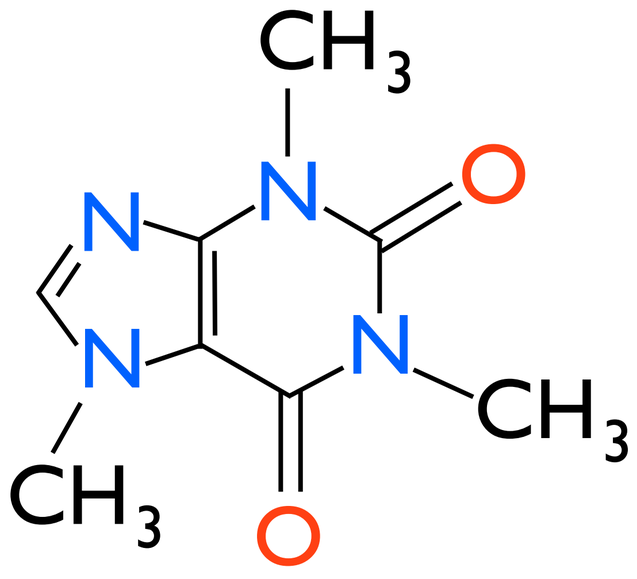


Engineering Programmed Evolution

Programmed Evolution

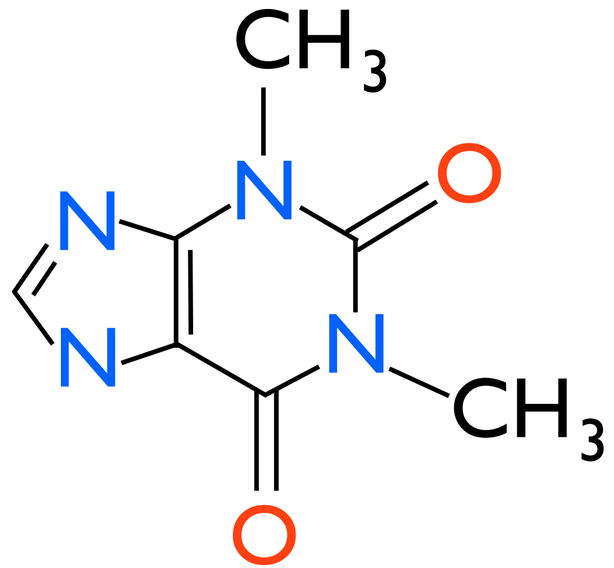


How to Build a Biosensor



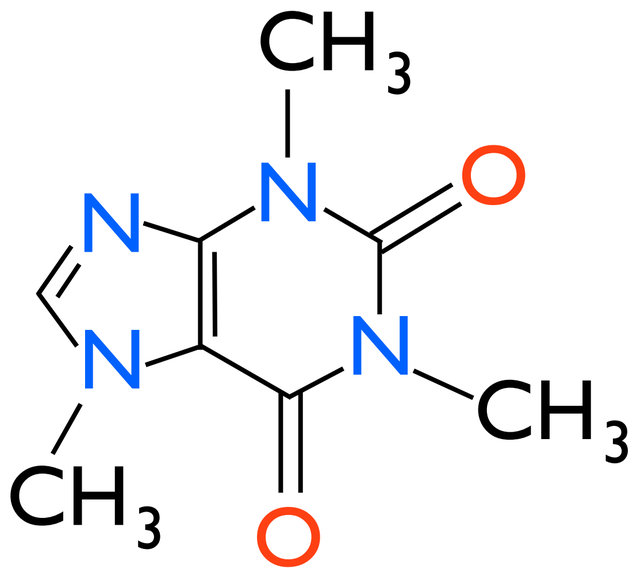
caffeine

CDM



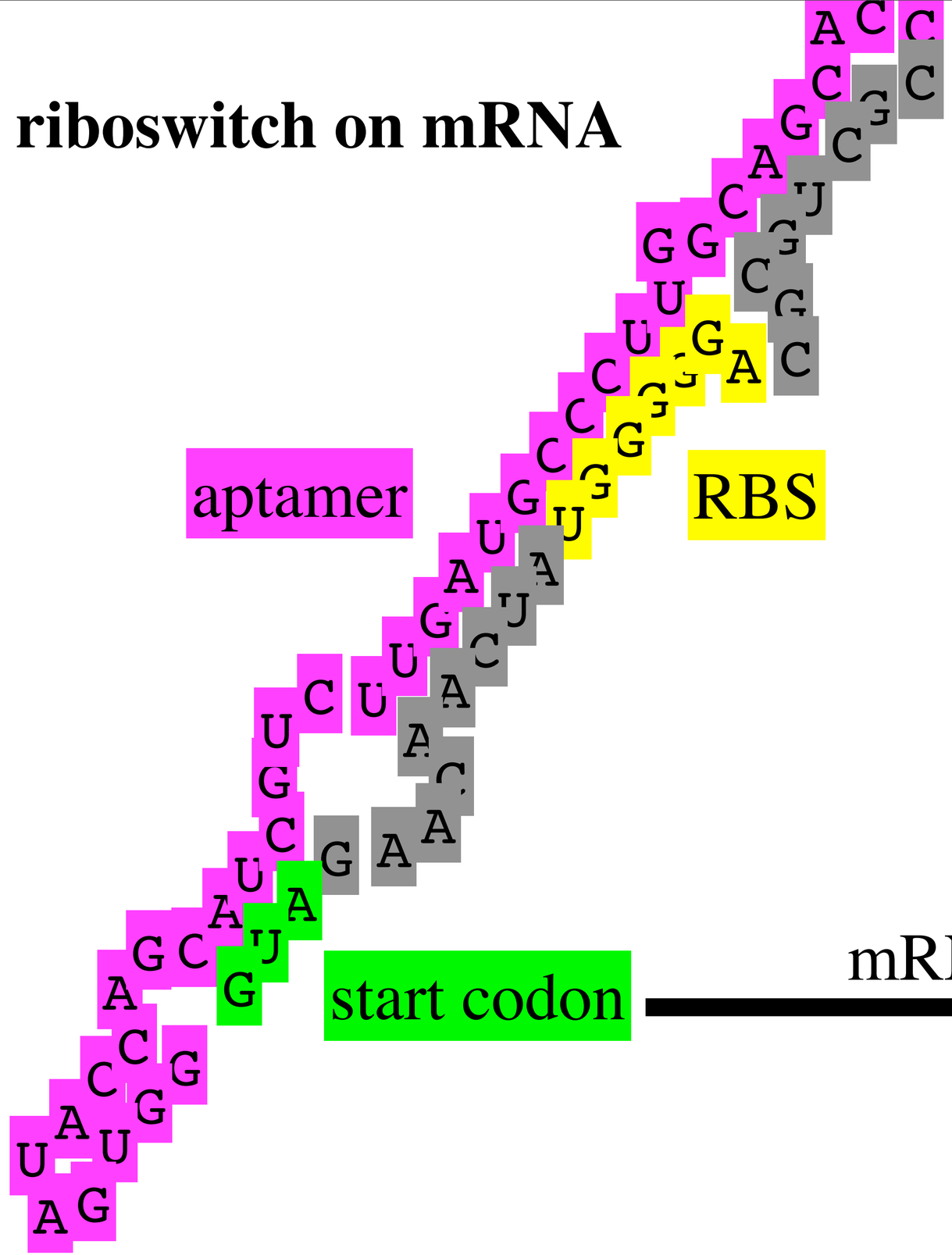
theophylline

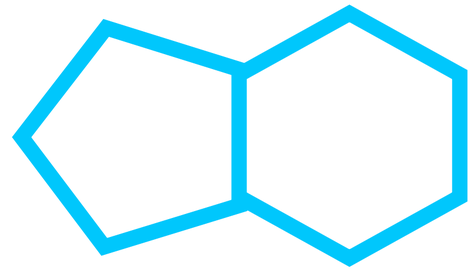
How to Build a Biosensor



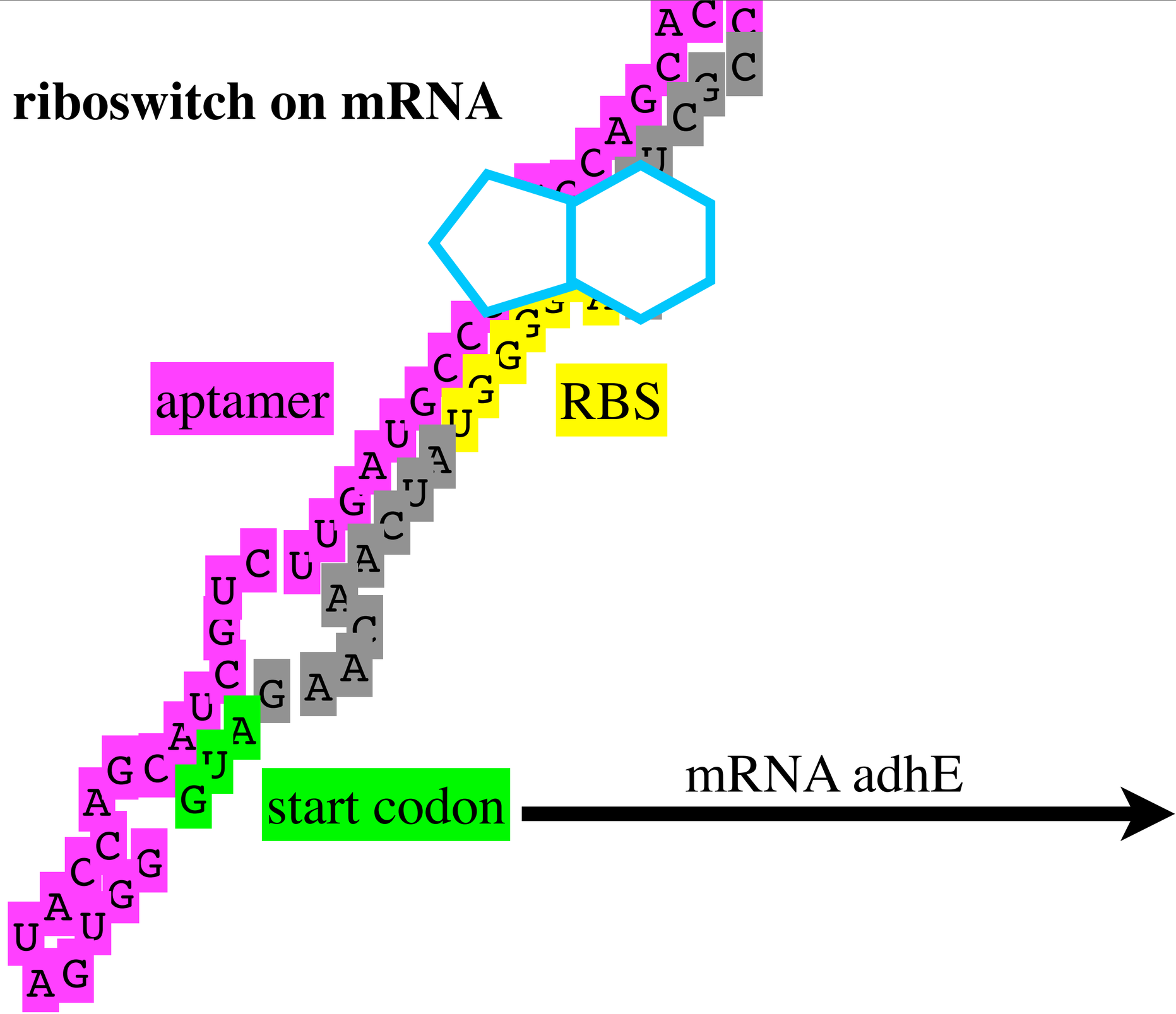
caffeine

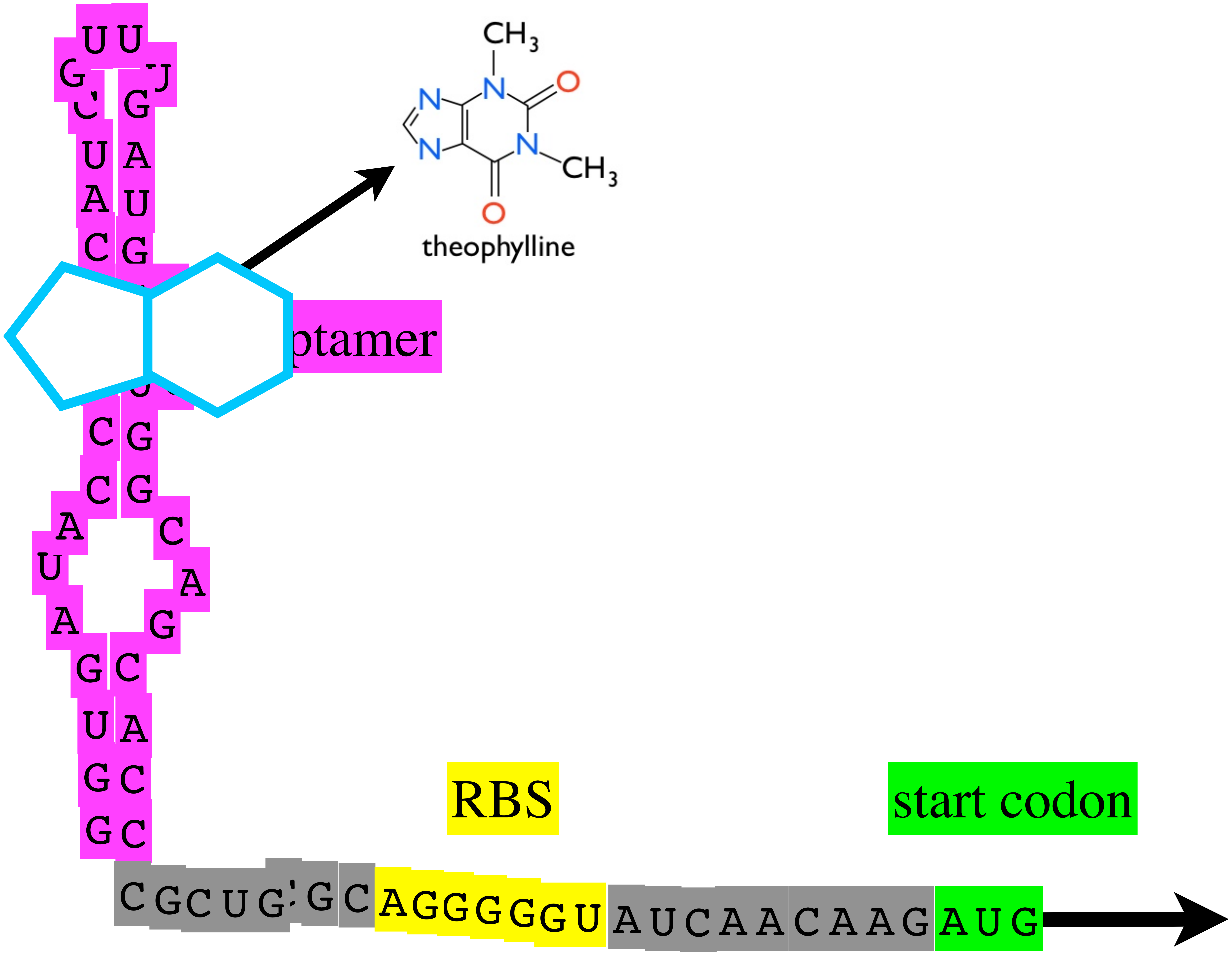
riboswitch on mRNA



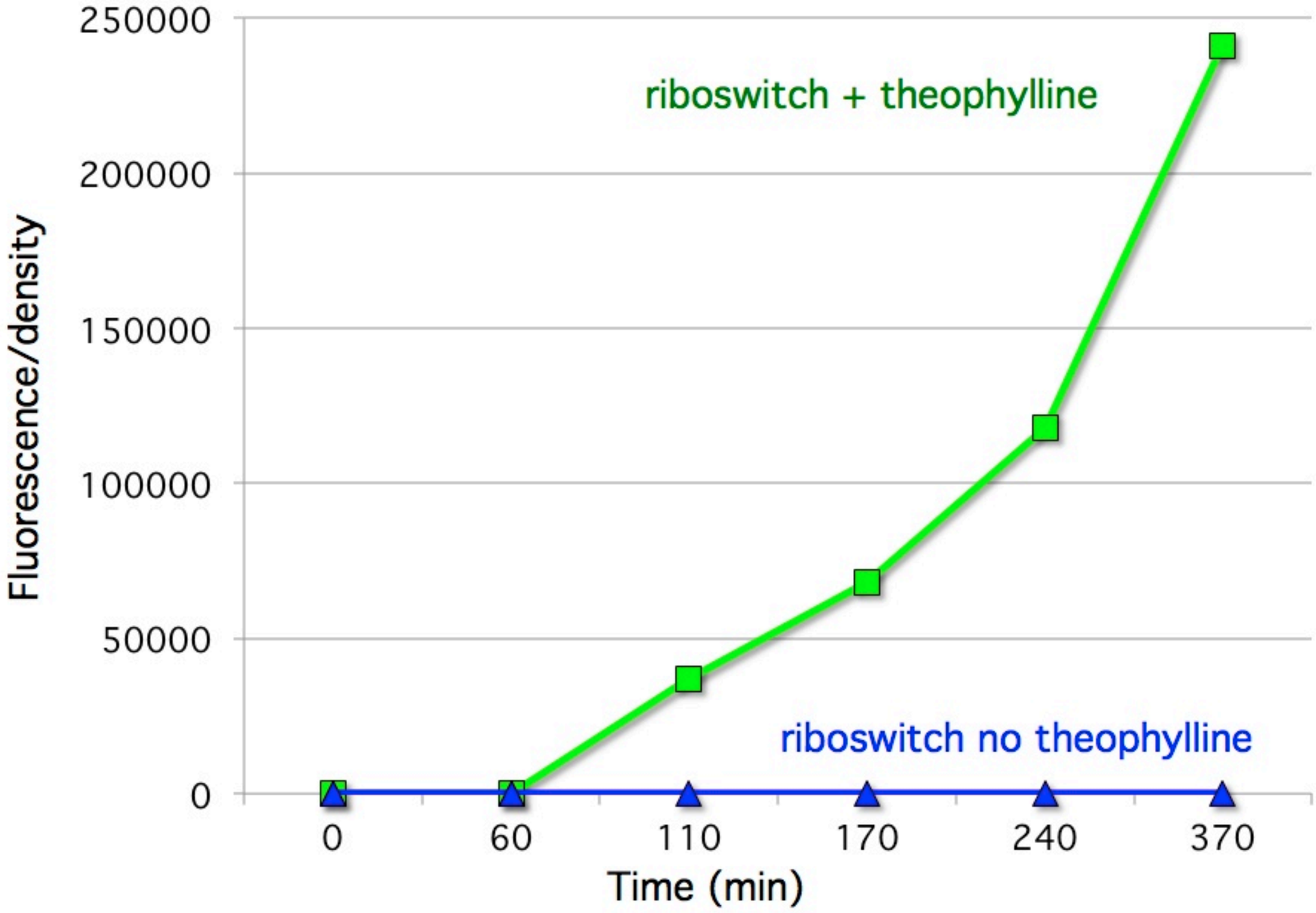


riboswitch on mRNA

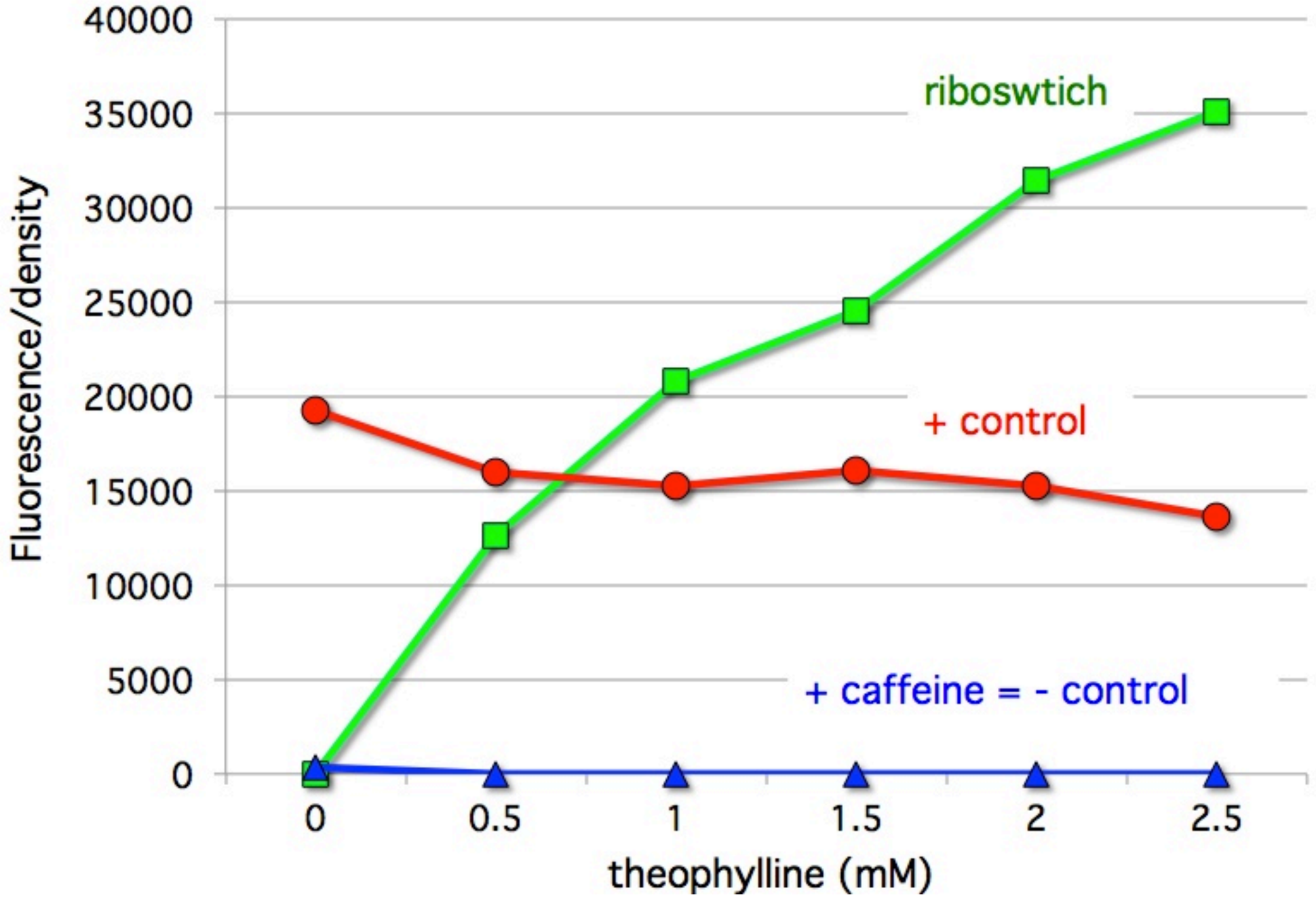



CH3
CH3
theophylline
ptamer
RBS
start codon
AUCAACAAG
AUG

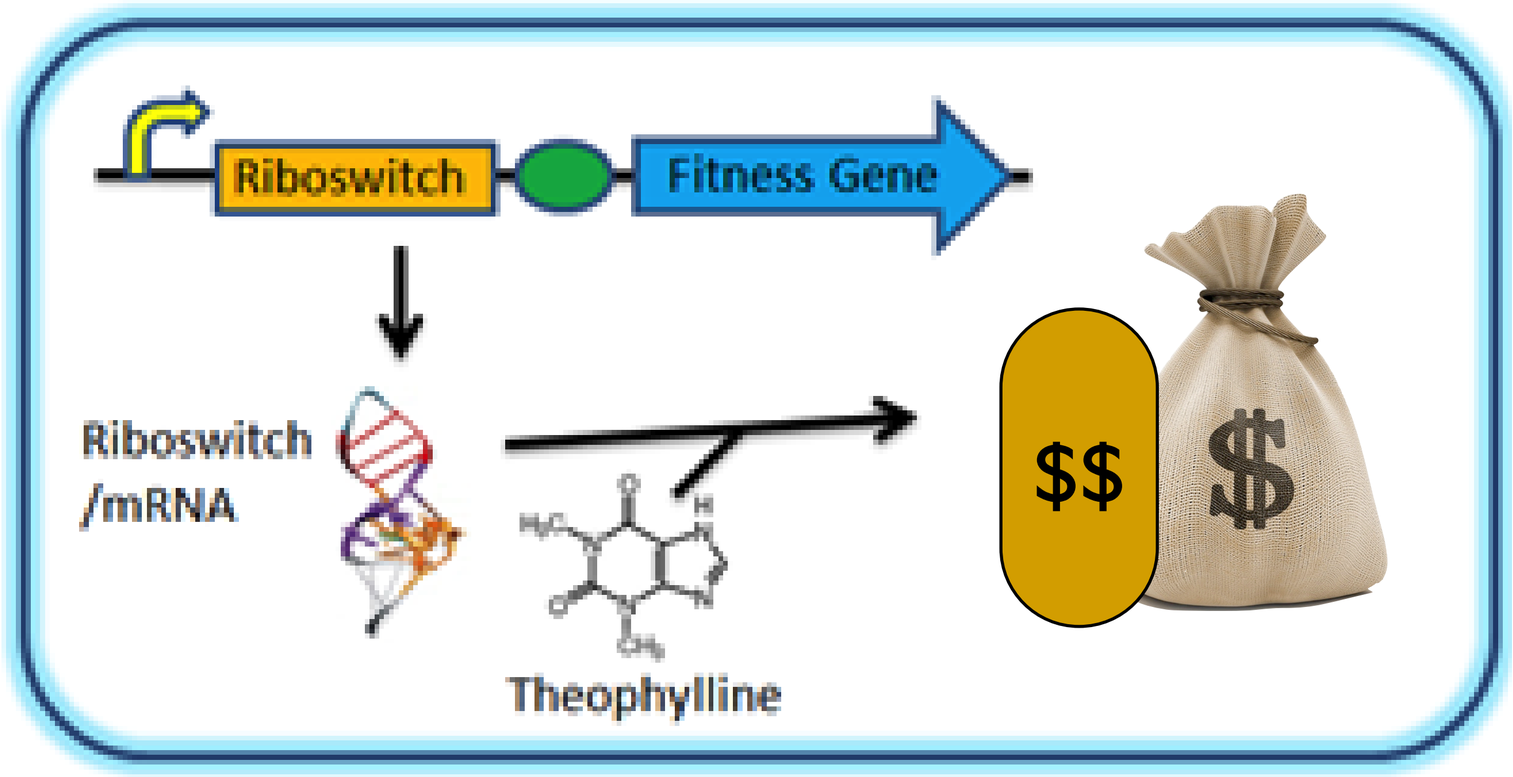
Biosensor Detects Theophylline



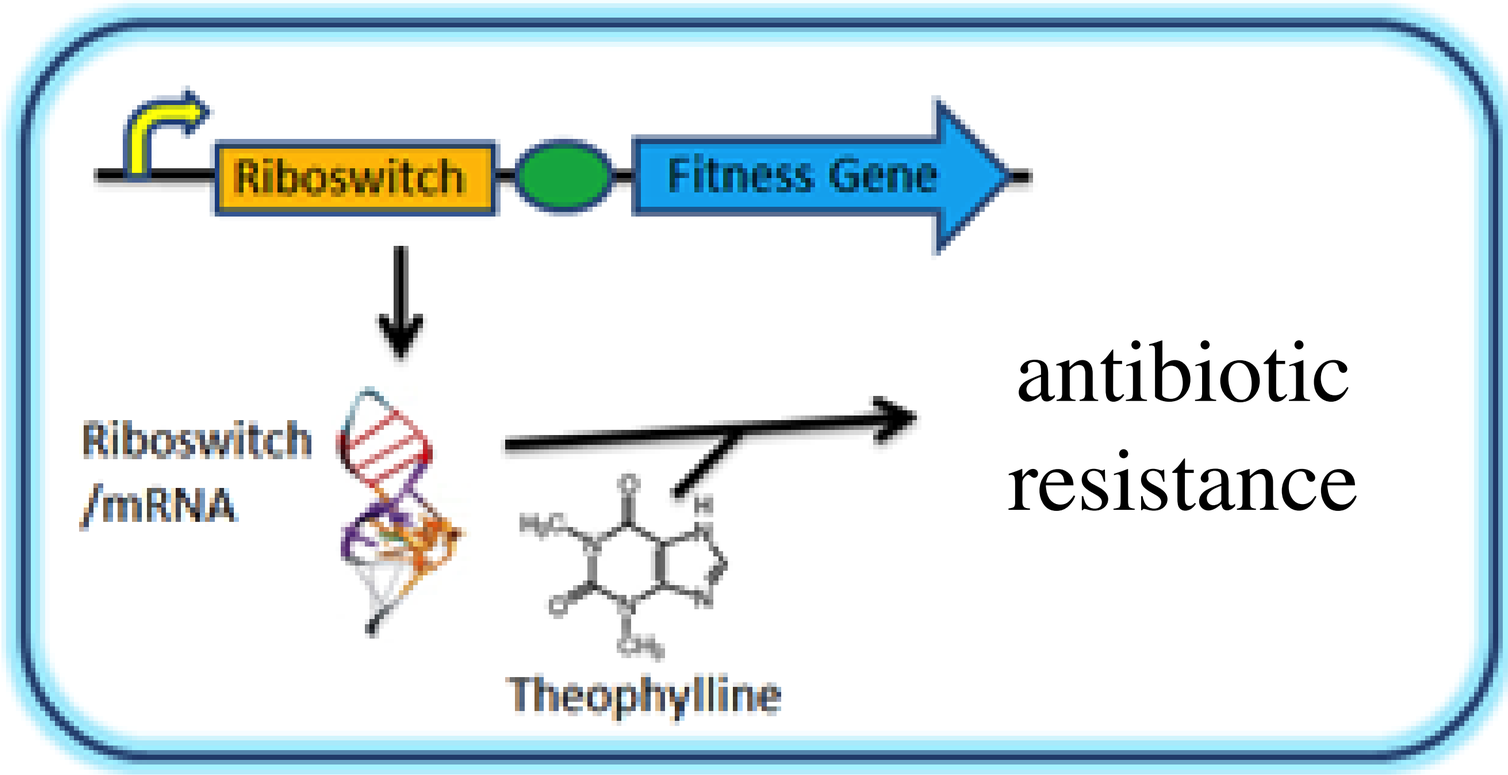
Biosensor Detects Theophylline



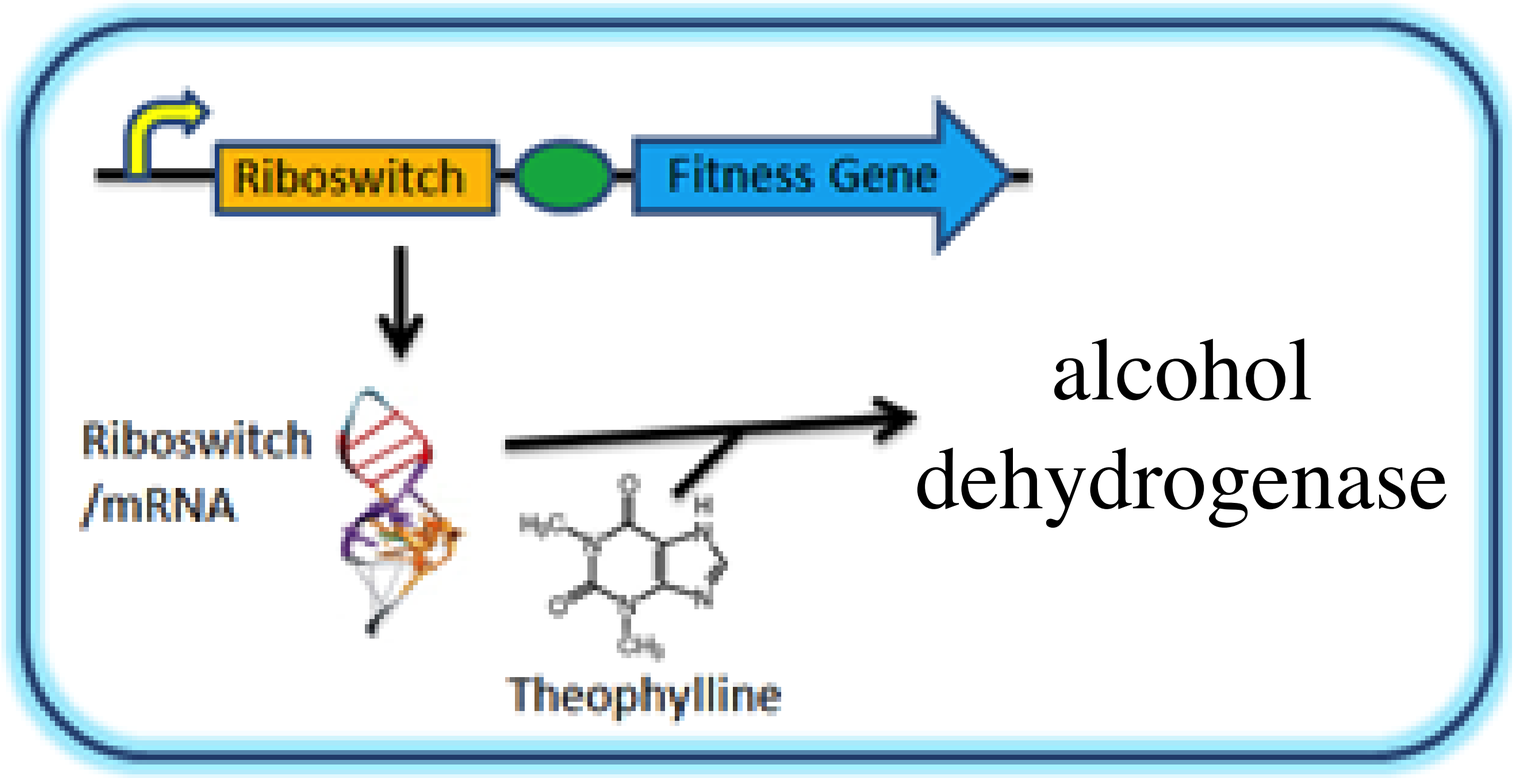
Fitness Module



Fitness Module



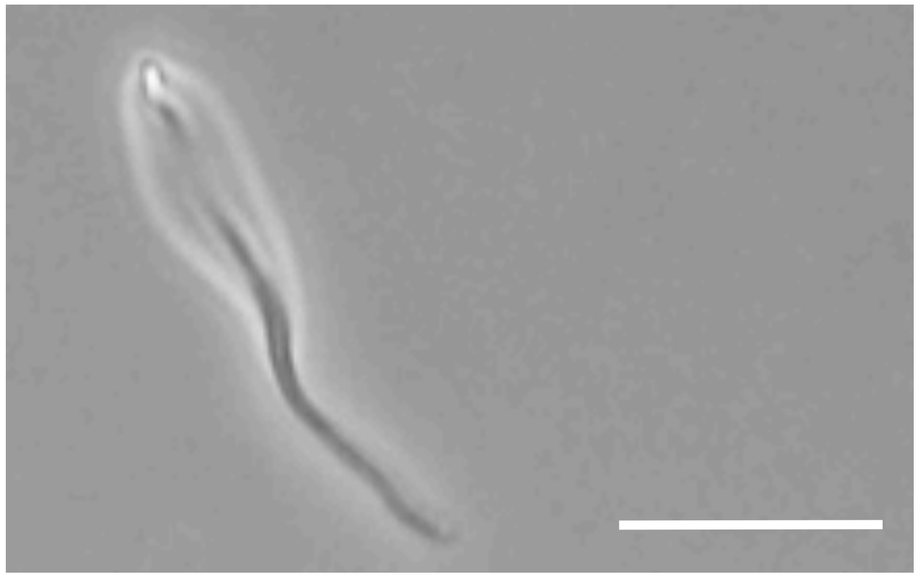
Fitness Module



Develop New Fitness Module

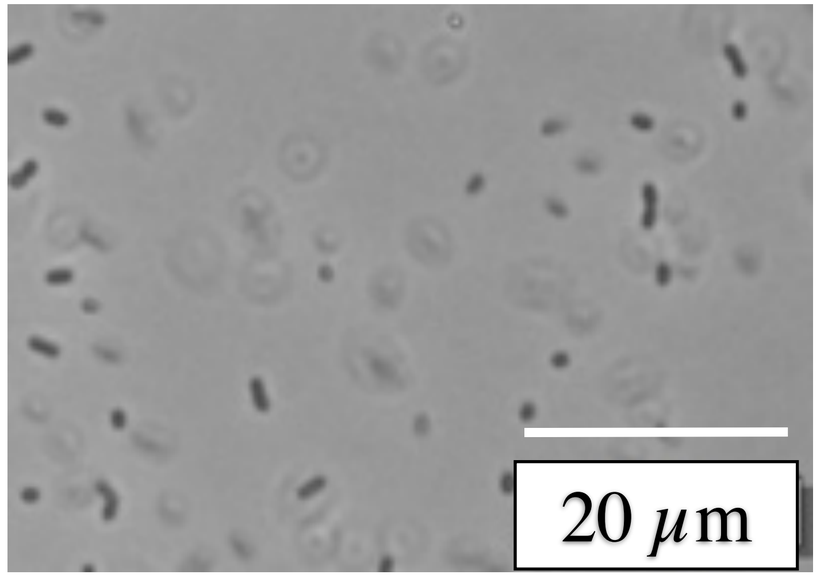
Elizabeth Brunner ’16

thyA^{-} mutant



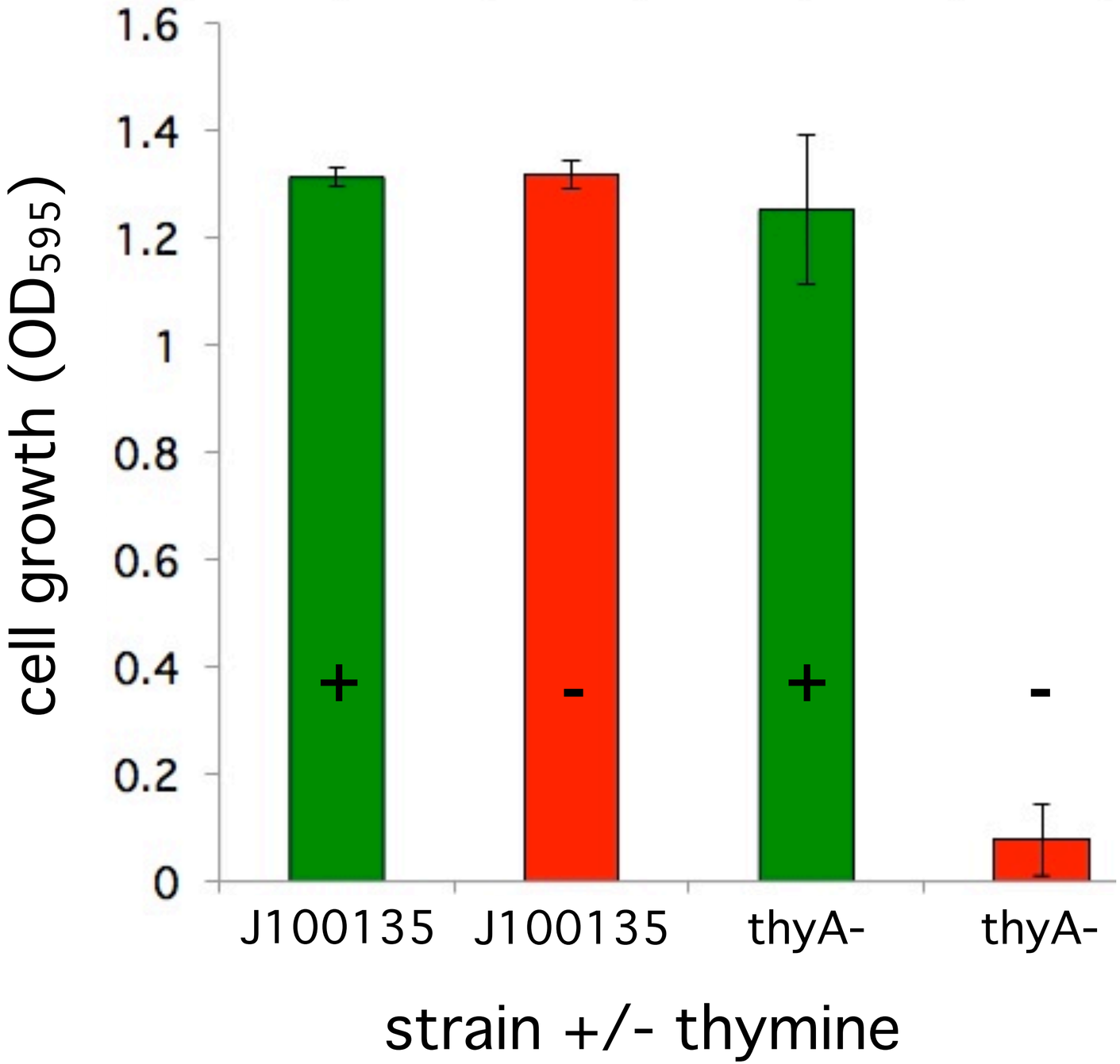
no DNA synthesis
no cell division

J100135



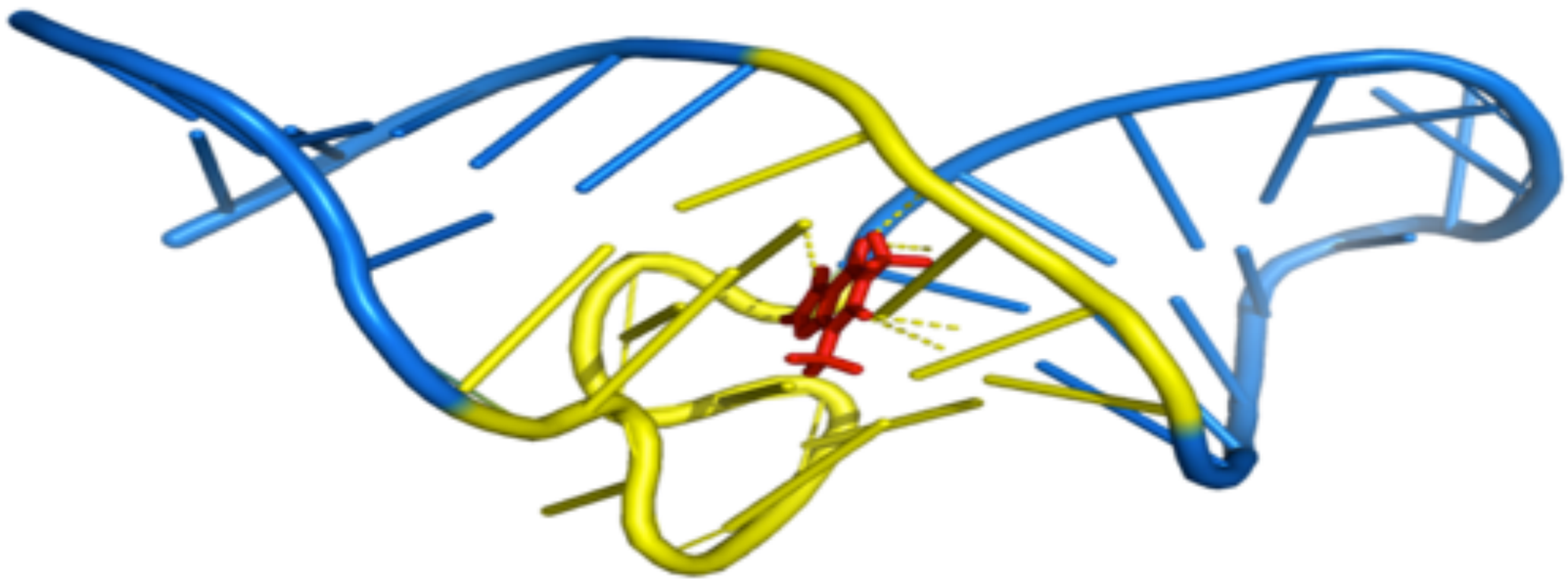
thyA^{-} mutant
+ *thyA* transgene

thyA Fitness Module



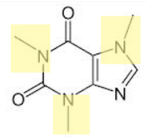
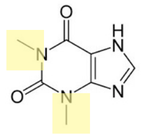
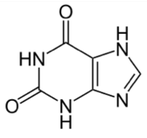
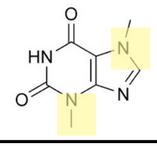
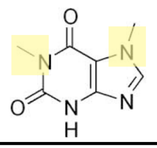
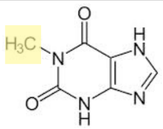
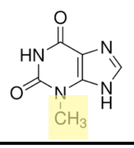
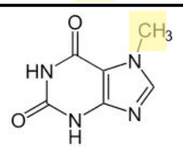
Can We Make New Riboswitches?

Catherine Doyle ’14

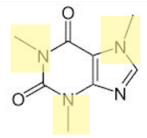
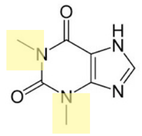
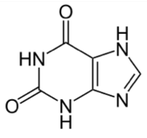
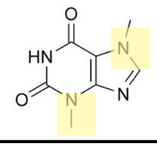
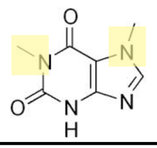
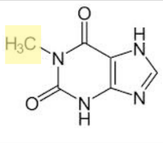
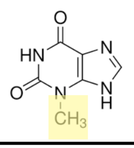
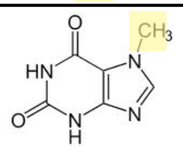


theophylline aptamer

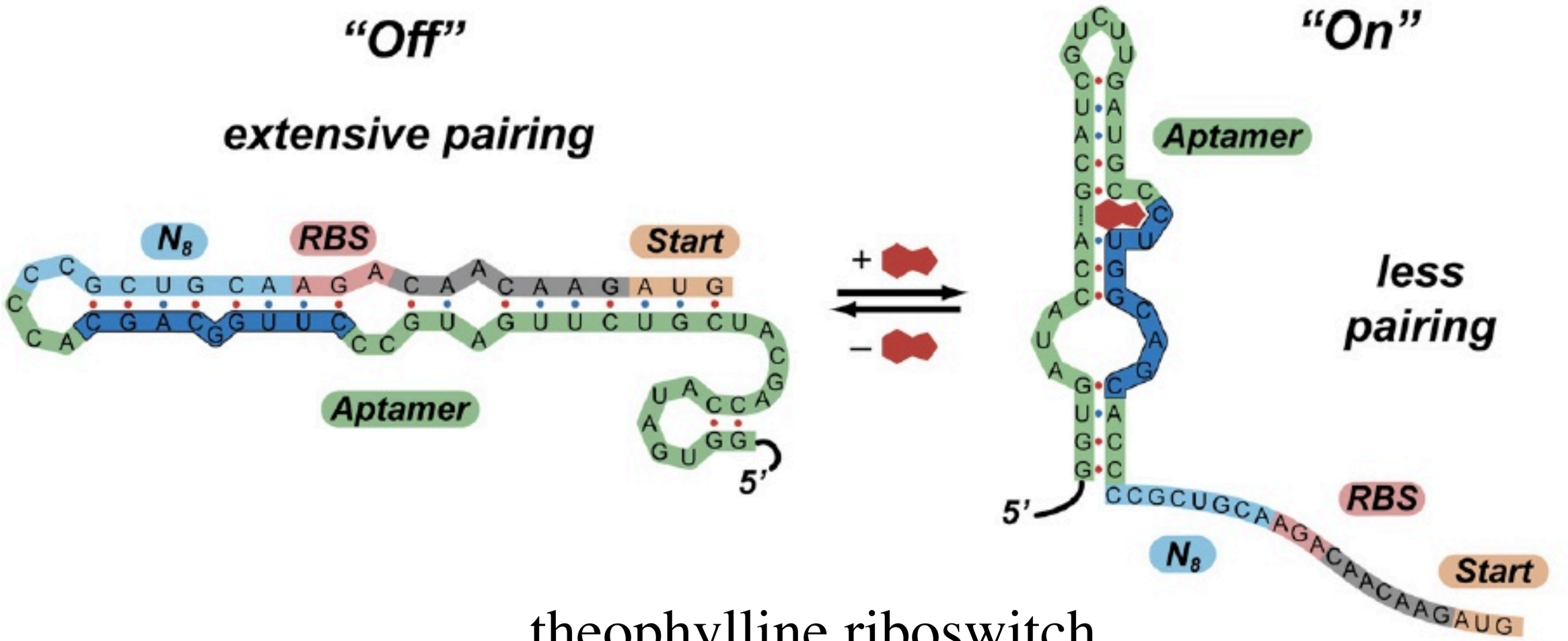
Make New Riboswitches

Name	Structure	Aptamer?	Riboswitch?
caffeine		yes	no
theophylline		yes	yes
xanthine		yes	no
theobromine		no	no
paraxanthine		no	no
1-methylxanthine		no	no
3-methylxanthine		yes	no
7-methylxanthine		no	no

Make New Riboswitches

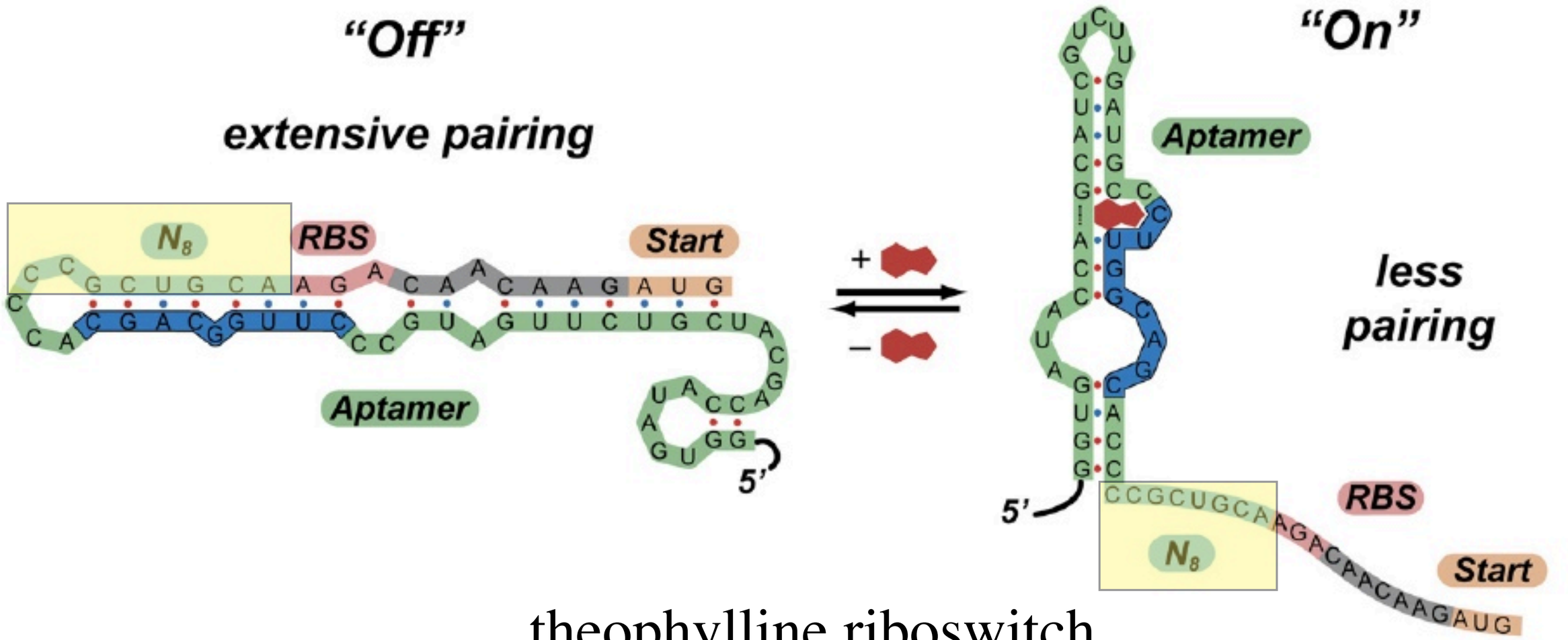
Name	Structure	Aptamer?	Riboswitch?
caffeine		yes	no
theophylline		yes	yes
xanthine		yes	no
theobromine		no	no
paraxanthine		no	no
1-methylxanthine		no	no
3-methylxanthine		yes	no
7-methylxanthine		no	no

Can we design new riboswitches?



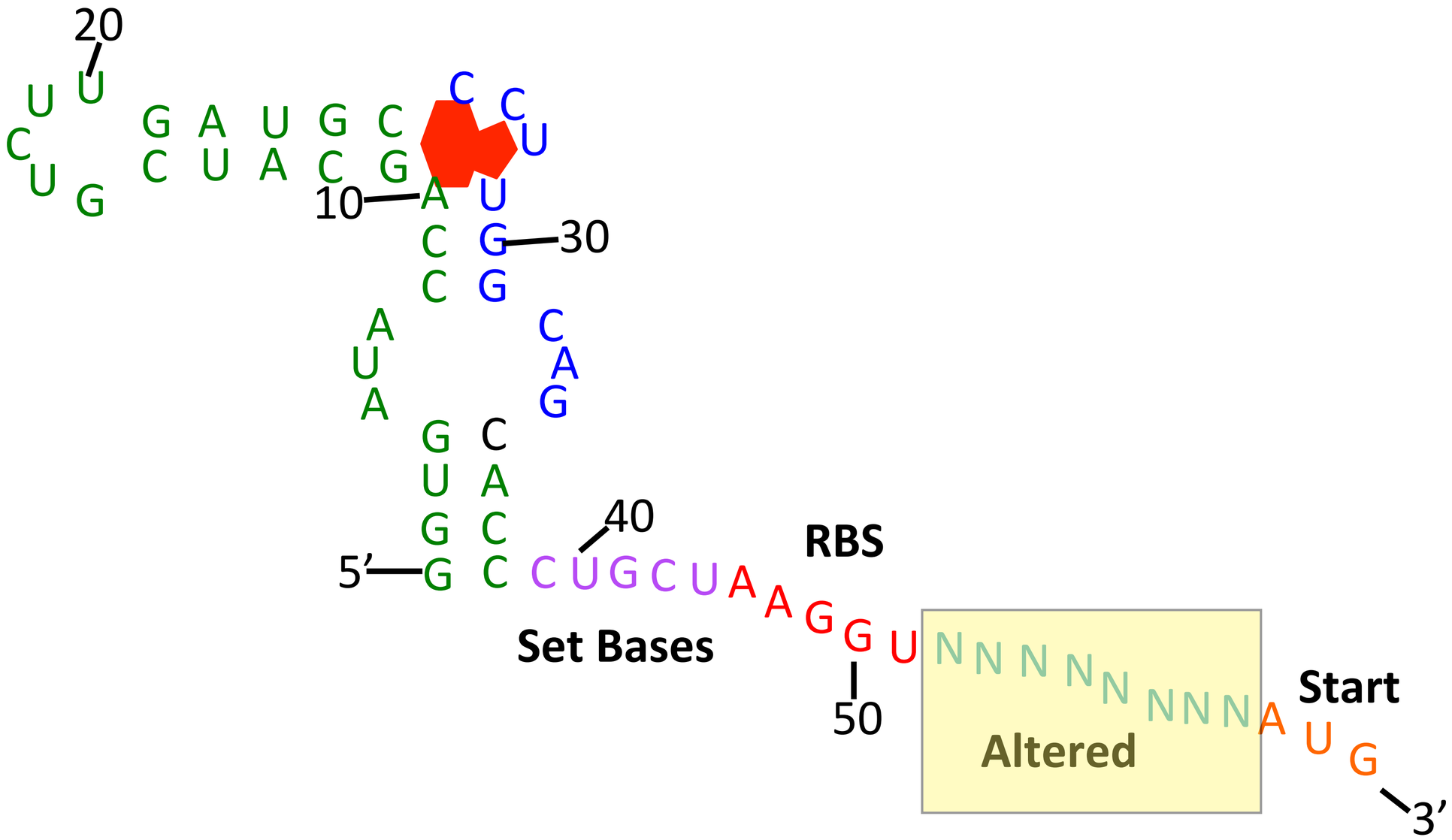
theophylline riboswitch

Can we design new riboswitches?

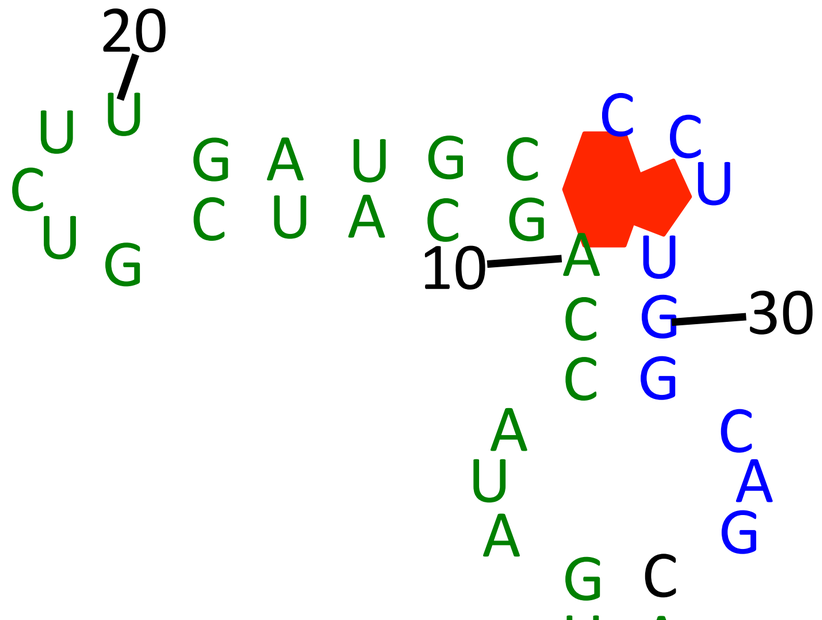


theophylline riboswitch

Optimizing Riboswitches

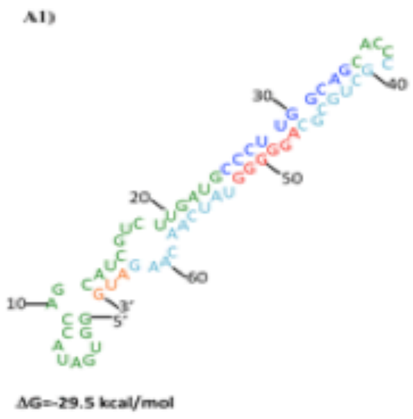


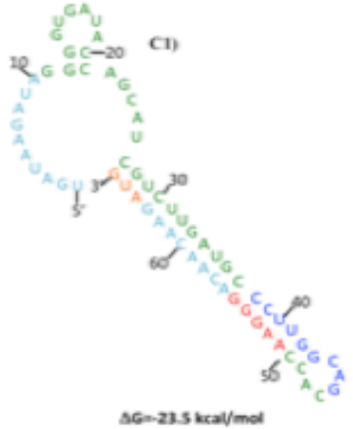
Optimizing Riboswitches

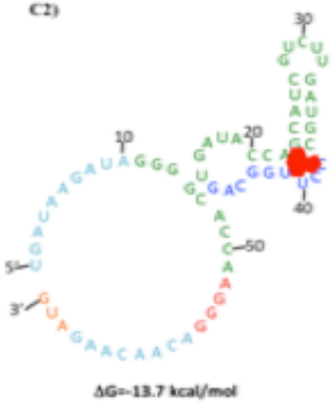


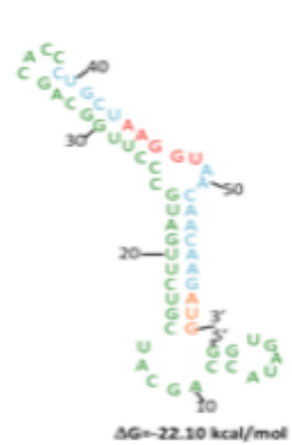
$4^9 = 262{,}144$ combinations

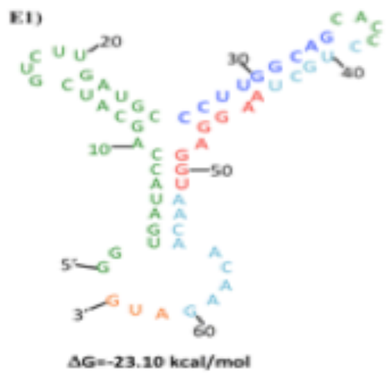
Fold Candidate Riboswitches

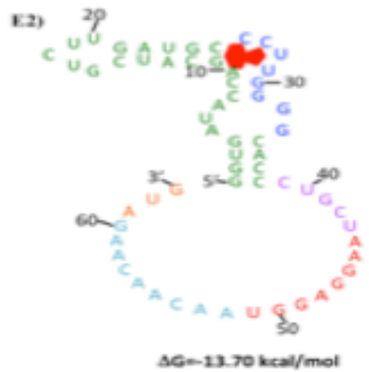












calculate free energy

Python Scripts for *in silico* Screening

aptamer sequence

↓

generate 1st riboswitch

↓

generate 262,144 riboswitches

↓

fold, calculate ΔG, no ligand

↓

fold, calculate ΔG, + ligand

↓

select riboswitches ΔG difference

↓

confirm base pairing

Python Scripts for *in silico* Screening

aptamer sequence

↓

generate 1st riboswitch

↓

generate 262,144 riboswitches

↓

fold, calculate ΔG, no ligand

↓

fold, calculate ΔG, + ligand

↓

select riboswitches ΔG difference

↓

confirm base pairing

8 theophylline

17 caffeine

What's Next?

✓ make all 25 candidate riboswitches

✓ test candidate riboswitches

incorporate *thyA* fitness module

optimize CDM production

publish paper

buy beach house in Caribbean

What is the secret to success?

“Would you like me to give you a formula for success? It's quite simple, really. **Double your rate of failure.** You are thinking of failure as the enemy of success. But it isn’t at all. You can be discouraged by failure or you can learn from it, so go ahead and make mistakes. Make all you can. Because remember, that’s where you will find success.”

Thomas J. Watson
Founder of IBM

The scenery only changes for the lead dog.

The scenery only changes for the lead dog.

Acknowledgements

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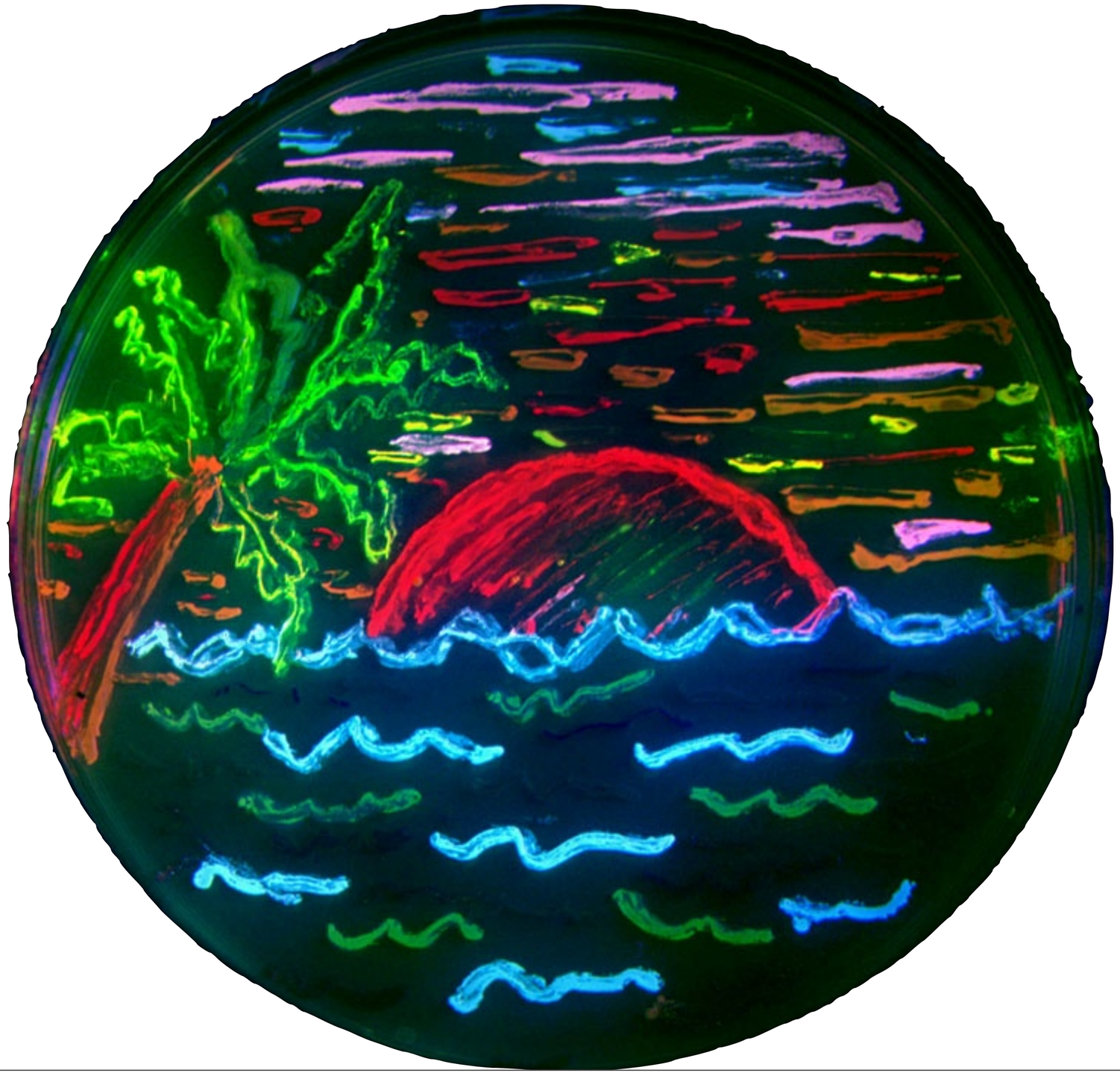
The Duke Endowment, NSF, HHMI
Genome Consortium for Active Teaching (**GCAT**)
Davidson College James G. Martin Genomics Program
MWSU SGA, Foundation & Summer Research Institute

The End

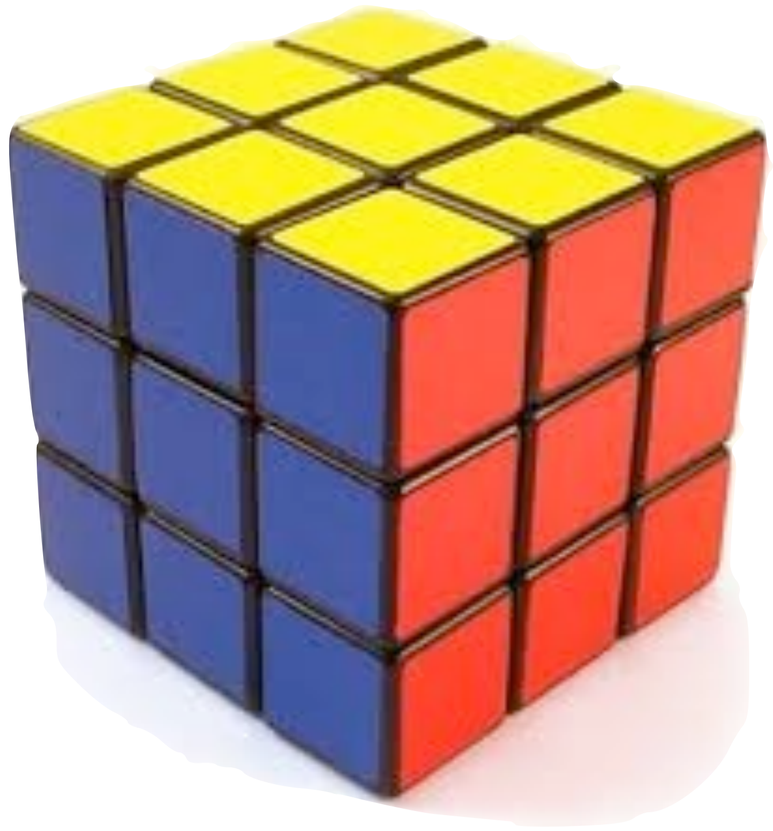


Math Modeling of Programmed Evolution

metabolic flux = f(promoter, RBSs, alleles, # plasmids)

humans

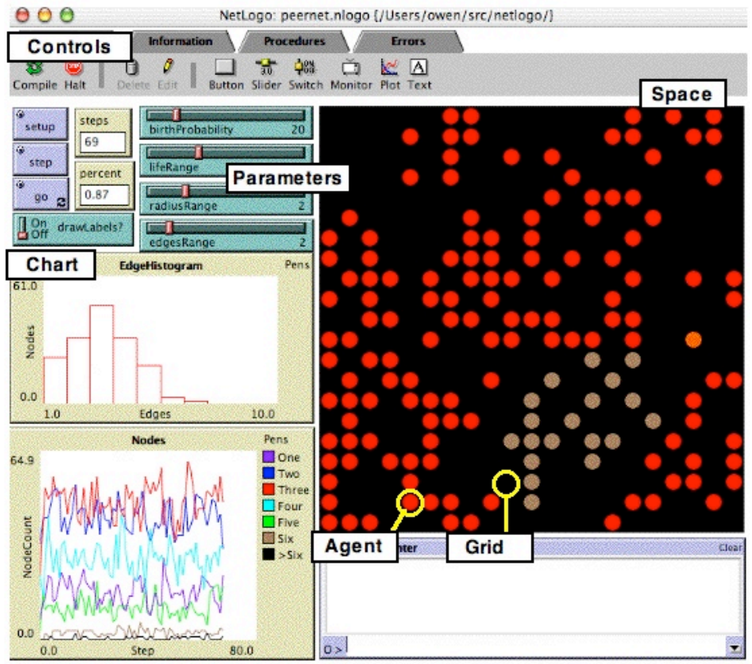
bacteria

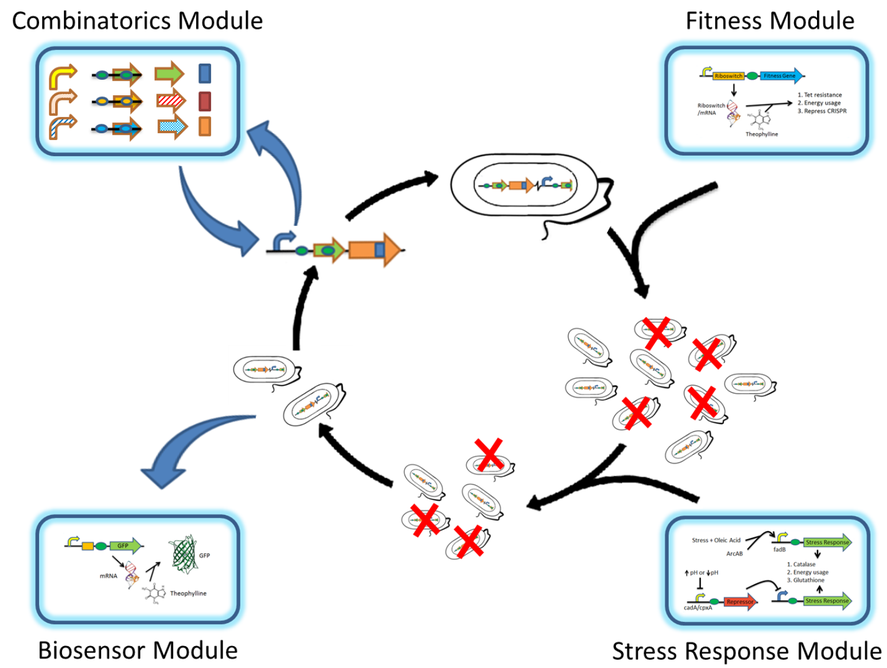


searching multi-dimensional space

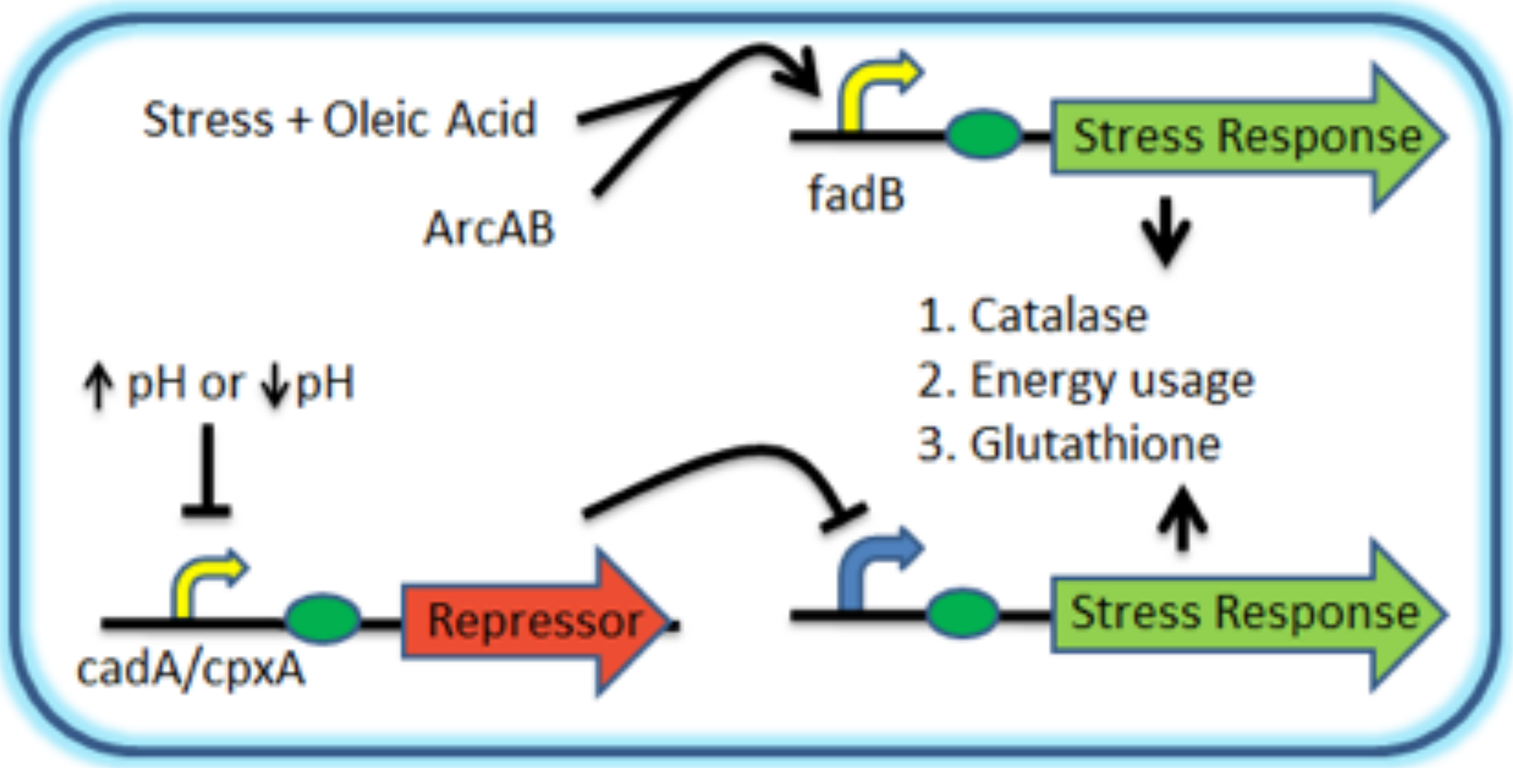
Agent-Based Models of Programmed Evolution

NetLogo

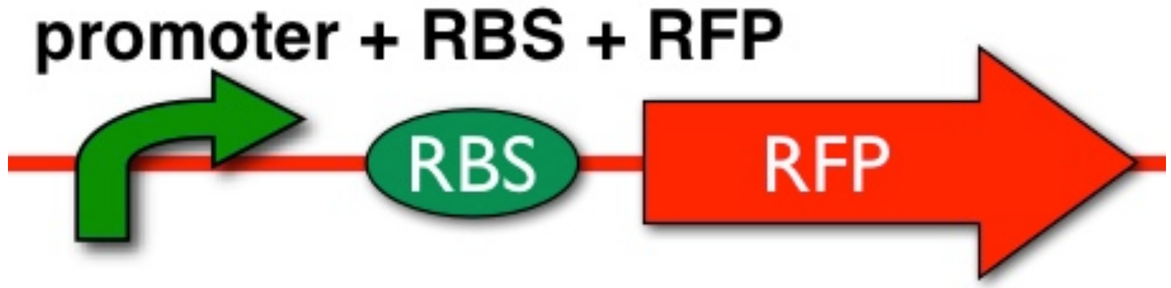




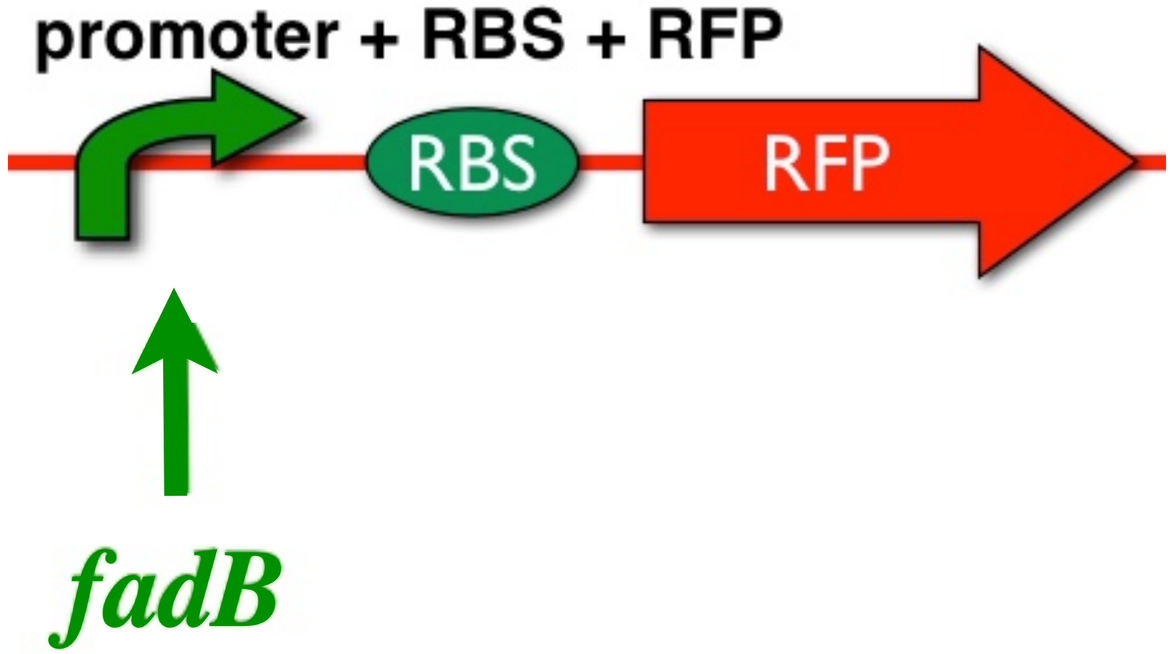
Stress Response Module



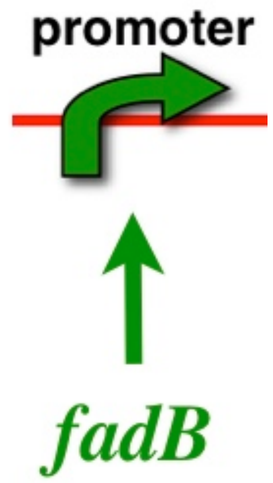
Engineering a Stress Module



Engineering a Stress Module

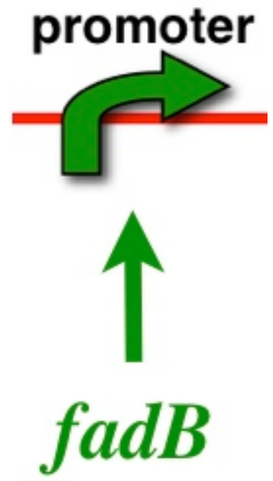


Engineering a Stress Module



AATTCGCGGCCGCTTCTAGAGATCGGCATTTCTTTAATCTTTTGTTTGCATATTTTTAACACAAAATACACACTTCGACTCATCTGGTACGACCAGATCACCTTGCTACTAGTAGCGGCCGCTGCA
GCGCCGGCGAAGATCTCTAGCCGTAAAGAAATTAGAAAACAAACGTATAAAAATTGTGTTTTATGTGTGAAGCTGAGTAGACCATGCTGGTCTAGTGGAACGATGATCATCGCCGGCG

Engineering a Stress Module



AATTCGCGGCCGCTTCTAGAGATCGG

ATTTCTTTAATCTTTTGTTTGCATATTTTTAACACAAAATACACACTTCGACTCATCTGGTACGACC

ACGTCGCCGGCGATGATCATCGTTCCACTAGA

GCGCCGGCGAAGATCTCTAGCCGTAAAGAAATTAGAAAACAAACGTATAAAAATTGTGTTTTATGTG

TGAAGCTGAGTAGACCATGCTGGTCTAGTGGAACGATGATCATCGCCGGCG

AATTCGCGGCCGCTTCTAGAGATCGGCATTTCTTTAATCTTTTGTTTGCATATTTTTAACACAAAATACACACTTCGACTCATCTGGTACGACCAGATCACCTTGCTACTAGTAGCGGCCGCTGCA
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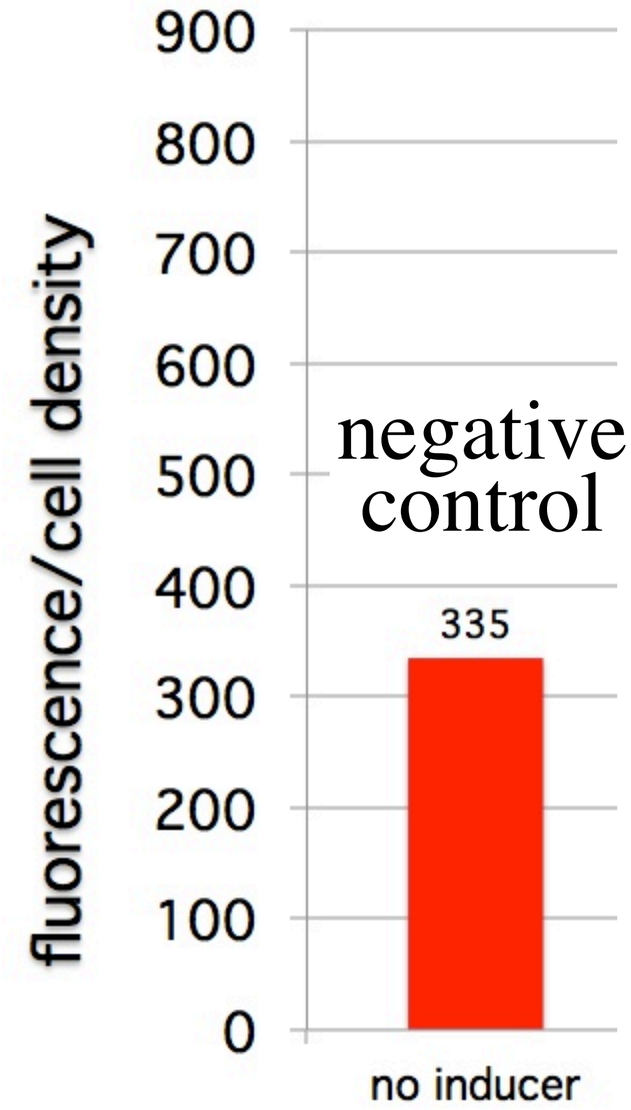
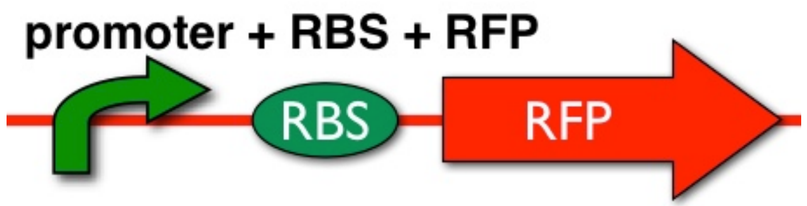
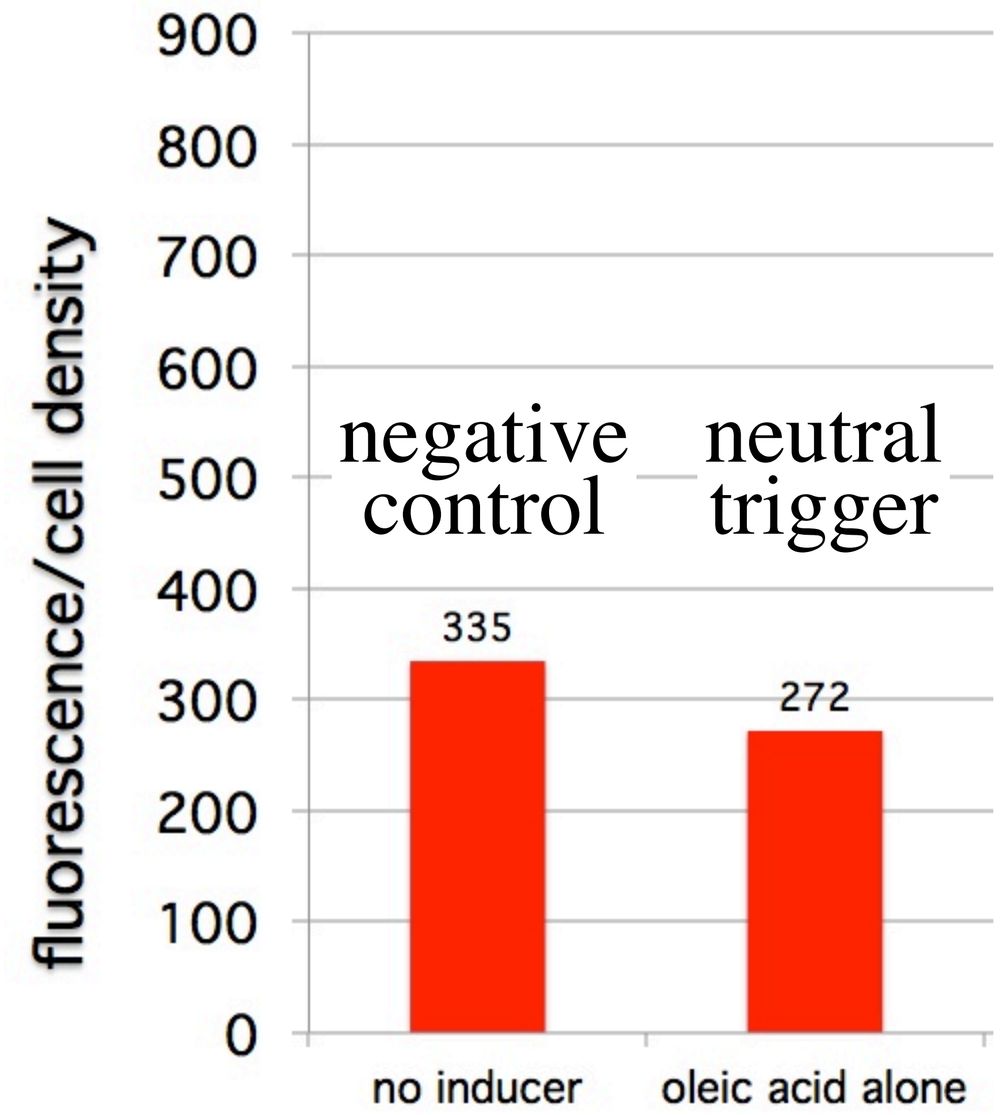
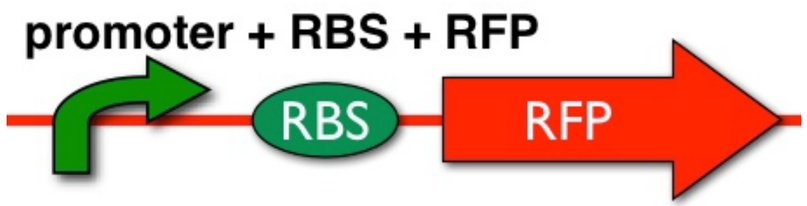
Testing Stress Module



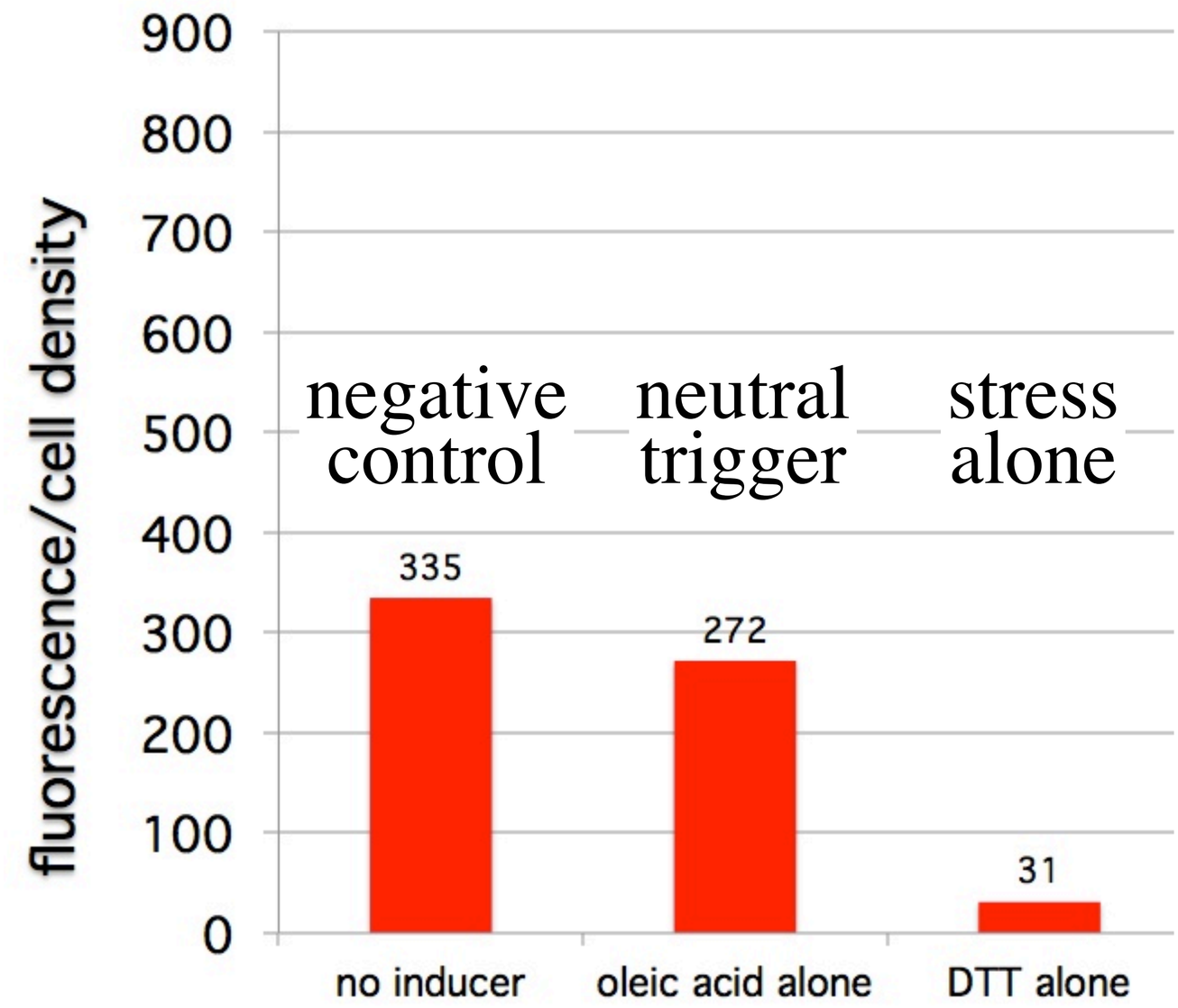


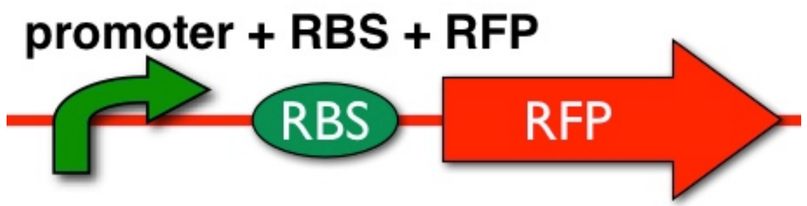
Testing Stress Module



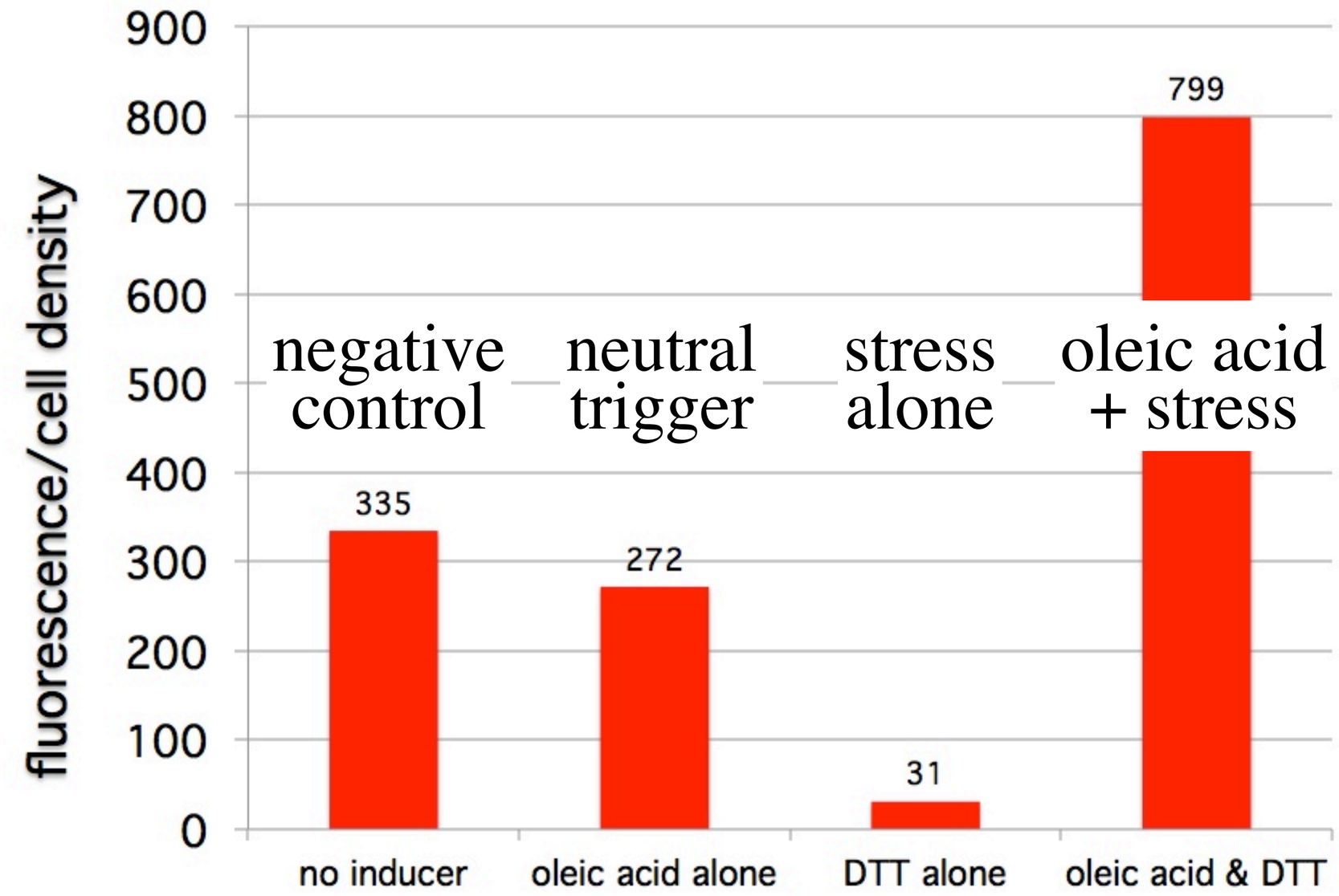


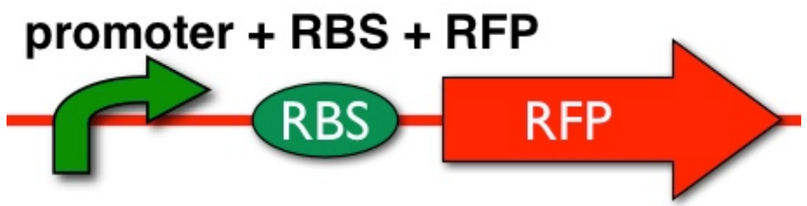
Testing Stress Module





Testing Stress Module





Testing Stress Module