



Rhythmic Sharing

An Astrocyte-Inspired Algorithm for Robust Learning of Evolving Dynamical Systems with Applications in Anomaly Detection

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Washington, DC • January 4–7

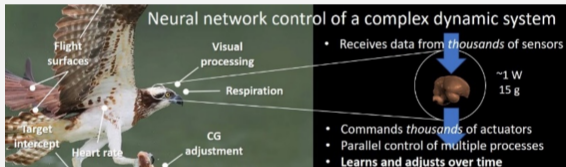
Overview

Summary – Neuromorphic Algorithms

K \ m X c k Y ` c c _ l c h Y V f U j b k \ Y b X y Y c d j b [U [c f] h a g 3

Summary – Neuromorphic Algorithms

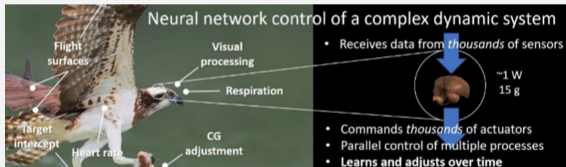
K \ m X c k Y ` c c _ l e h Y V f U b k \ Y b X Y j Y c d] b [U [c f] h a g 3



From: ResCon LLC

Summary – Neuromorphic Algorithms

K \mXc kY`cc_ lc h YVfUbk \YbXy Ycd]b[U[cf]h a g3



From: ResCon LLC

H YVfUbc i hYfZcfa ga UW]bY`YUfb]b[]bgYj YfU hUg g]bW X]b[.

`YUfb]b[UbXYI hUdc`U]b[Zca `ja]hXXUk]h X] YfYbha cXU]hYg]UbXz

Ub]M]U]b[zXYhV]b[zUbXU]Ld]b[lc WbWdhX]z

Summary – Our Lab

@cgYfh@Uvkcf_gcbh Y]bMfgYV]cbcZbYi fcgV]MbWfYgYUfW
UbXWVa di hU]cb"K YfY]bMfYghX]b

UghcV]hYgUgV]bXi V]cfcgZbYi fcbU V] b]hcb

\nM]XgnghYa gh UhVa V]bYbYi fcbU W]hi fYgUbXX]]U
WVa di hMfg

BYi fca cfd\]WU[cf]h a gh Uhi b]Zh Ycf]YgcZbYi fU V] b]hcb
UbXWVa di hU]cb

Summary – Our Lab

@cgYfh@Uvkcf_gcbh Y]bHfgYV]cbcZbYi fcgV]bWfYgYUfW
UbXWVa di hU]cb"K YfY]bHfYghX]b

UghcV]hYgUgV]bXi V]cfcgZbYi fcbU V] b]hcb

\nM]Xng]hYa gh UhVa V]bYbYi fcbU W]h fYgUbXX]]HU
WVa di Hfg

BYi fca cfd\]WU] cf]h a gh Uhi b]Zh Ycf]YgcZbYi fU V] b]hcb
UbXWVa di hU]cb

CbYcZh YgYU] cf]h a g]gf\n]h a]W]U]b] ZhcXUng]hcd]W

This Presentation

HexXlně="XlgWgg

% ħ YUghfcWdhWbgd]fUhcZci ff\nħ a]Wg\Uf]b[U[cf]ħ a ž

&' ħ Yf\nħ a]Wg\Uf]b[U[cf]ħ a ž

' " \ck ci fU[cf]ħ a Yb\UbWgXf]Zh]bUXUHgMžUbXħ YfYgi ħcZ
Wa V]b]b[f\nħ a]Wg\Uf]b[k]ħ VebWdhXf]ZhXYhWcfcgžUbXž

(" \ck Ug]b[Yf\nħ a]Wg\Uf]b[]bgħUbWVWb YUfbUbXYI ħUdc UħY
ħc X] YfYbhXhbUa]Wgk\]Y9GBgWbbch'

Biological Inspiration

The Brain: Not Just Neurons

AcghbYi fca cfd\]Wá UW]bY`YUfb]b[U[cf]h a gUfY]bgd]fYXVm
bYi fcbgcfWá di hYj]Ugd]_]b["

The Brain: Not Just Neurons

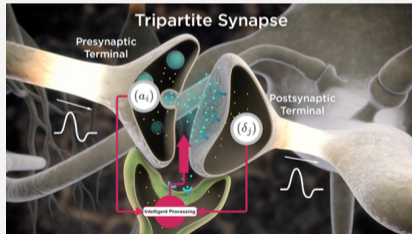
AcghbYi fca cfd \ JVa UW]bY`YUfb]b[U[cf]h a gUfY]bgd]fYXVm
bYi fcbgcf WVa di hYj]Ugd]_]b["

<ck Yj Yf **neurons are not the only cells**]bh YVfU]bUbX **not all
cells communicate through spiking!**

Ch YfW`g]bh YVfU]bd`UhUb YggYbh]U UbXi bXYfghi X]YXfc`Y]b
W[b]h]cb"

Astrocytes and Glial Cells

5gdfcVhVgUFY[]UW`g|bj c j YX]bW[b]hcbh fci [\ h Y
hf]dUfh]YgnbUdgY00)



Astrocytes and Glial Cells

H fci [\ h Yhf]dUfh]hY gnbUdgYžUghfc VhYgUfYYggYbh]U hc
W[b]hcb.

9UWUghfc VhY]gVbbYhXlc Vhk Yyb &+ \$\$\$\$ UbX&a]`]cbgnbUdgYgž
WcfX]bU]b[UbXa cb]cf]b[h Ya C&Q

5bUghfc VhYVb VY]bVYX]Vmc]b[žVbbYh]b[hc gdU]U`nXghUbh
bYi fcbg

H YUghfc VhYgfygdcbXlc h YVcXngg]U]YUbXlc Yl hfbUgh]a i `U]cbOQ

Astrocytes and Glial Cells

H fci [\ h Yhf]dUfh]h YgnbUdgYžUghfc VhVgUfY YggYbh]U hc
W[b]hcb.

9UWUghfc VhV]gVbbYVhXlc Vhk Yyb &+ \$\$\$\$ UbX&a]`]cbgnbUdgYgž
WcfX]bU]b[UbXa cb]cf]b[h Ya C&Q

5bUghfc VhVWb VY]bVhX]Vmc]b[žVbbYV]b[hc gdU]U`nX]ghU
bYi fcbg

H YUghfc VhVgfygdcbXlc h YVcXnggdU]UbXlc Yl hfbUgh]a i `U]cbOQ

CbYkUhh YndchYbh]U`mVb]fc`bYi fcbg]gh fci [\ **rhythmic,**
physical forces cbh YgnbUdgYgQ QH]g]bgd]fYXh Yf\nh]a]W
g\U]b[U[cf]h a "

Rhythmic Sharing

RS Algorithm

H\Yf\m\ a]Wg\Uf]b[U[cf]h a k Ugcf][]bU`ndfcdcgYX]b? Ub[
UbX@cgyfh)Q

KYdfcdcgyXhk c \mlch\ YgYgUvci h\Yuf]b[]bbYi fcbgUzmf
cVgYfj]b[UghfcVhYg f\m\ a]WUMj]lm

@Yuf]b[]bj c j Ygf\m\ a]WYUf]U]cbg]b `]b_ gfyb[hžubXž

@Yuf]b[cVWfgj]UWcfX]bU]cbcbZh Yd\ UgYgcZh YgYf\m\ a]W
j Uf]U]cbg'

RS Algorithm

H\Yf\nh\ a]Wg\Uf]b[U[cf]h\ a k Ugcf][]bU`ndfcdcgYX]b? Ub[
UbX@cgyfh)Q

KYdfcdcgyXhk c \mlch\ YgYgUvci h\Yuf]b]b[]bbYi fcbgUzmf
cVgYfj]b[Ug]fcVh]Yg f\nh\ a]WUMj]]hm

@Yuf]b]b[]bj c j Ygf\nh\ a]WYUf]U]cbg]b]b_ gfyb[h žUbXž

@Yuf]b]b[cWwfgj]UWcfX]bU]cbcbZh Yd\ UgYgcZh YgYf\nh\ a]W
j Uf]U]cbg'

KY]a dYa Ybh\ YgY]bUfYgYfj c]fWa di h]b[a cXY

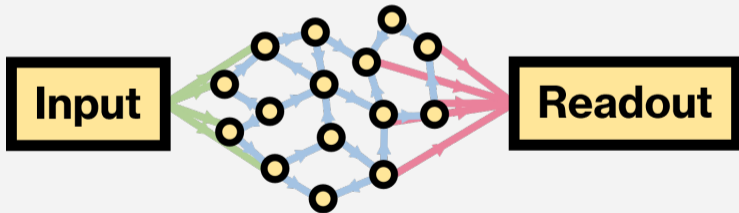
RS Algorithm – Reservoir Computing

FYgYfj c|fWa di hb| lg|bhf]WUHYm]b_YXlc bYi fcgVYbWzk \ YfY
]hk Ug fghXYj YcdYXUga cXYgcZgYbgcf]a chcf dfcWggYgO Q

H]ga U_Ygh Ya UbUi fU hZfcifa cXY`cZh Y]bhYUM]cbg
VYk YybUg]fcW]YgUbXbYi fcbg"

RS Algorithm – Reservoir Computing

H\YVUgYcZ\m\h a [Mg\Uf]b[lgUbYWc!gHUybYkcf_ k]\h
gdUfgYVcbbYVdj]hm



RS Algorithm – Node Update

: cf YUW h_a Y_{gh} Y_d h_a Y_j U_i Y_c Z_h Y_{bc} X_{Yg} | g_g Y_h Z_{Ug} Y_{Xcb} h_a Y_j U_i Y_{gc} Z_h Y_{bc} X_{Yg} U_b X_Y | b_{di} | g_h Y_n U_f Y_V | b_b Y_V | X_h "

d_{Uf} U_a Y_h U_l U_b X_h | g_h Y_j | b_{di} h_k Y_l | \ h_a U_f | f_g W_Y X_V n_U b_j | b_{di} h_k Y_l | \ h_a n_d Y_f !
| g_h Y_j | b_{di} h_k h_a Y_g n_h Y_a "

H | g_g | X_Y b_h | W_h U_b Y_W c_g h_U Y_b Y_h k_{cf} _ ž **with the exception of the modulated adjacency matrix** :

RS Algorithm - Oscillations

H Ya cXi UHXUXUWbWra Uf] Z bWjcbg\ckg\ck h Y
d\UgYgž žWbffc`h YgffYb[h cZh YbcXYg WbbWjcbg"

5?i flā ck!jbgd]fYXa cXY Wbffc`ggbwfcb]rUjcbczgi V[fci dgcZ
d\UgYgVUgYXcbh Y]bdi hGQ

RS Algorithm - Oscillations

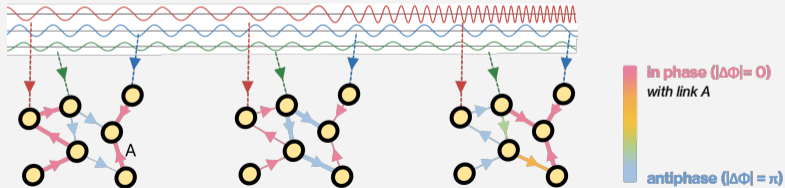
H Ya cXi UHXUXUWbWra Ufj]

Z bWjcbg\ckg\ck h Y

d\UgYgž žWbffc`h YgffYb[h cZh YbcXYg WbbWjcbg"

5?i flā ckc!jbgd]fYXa cXY Wbffc`ggbWfcb]nUjcbcZgi V[fci dgcZ

d\UgYgVUgYXcbh Y]bdi hΘQ



RS Algorithm - Oscillations

H |g|gh Y?i fUa c|c a cXYZ bW|cbh UhW|bfc`gh Yd\UgYgcZh Y
`b_g'

—

|gh YbU| fUZYei YbW|cZh YbcXYgž |gh Y`cW|a YUb YXž |gh Y
|b|X|bW|a Uf|ž UbX UfYWi d|b| \m|fdUfUa Y|f|gžUbX X|bch|g
YYa Yb|k |gYa i |hd|W|cb"

RS Algorithm - Oscillations

H |g|gh Y? i fUa c|c a cXYZ bW|cbh UhW|bfc`gh Yd\UgYgcZh Y
`b_g'

—

|gh YbUhi fUZYei YbW|cZh YbcXYgž |gh Y`cW|a Yub YXž |gh Y
|bV|X|bW|a Uf|ž UbX UYWi d|b[\m|fdUfUa Y|f|gžUbX X|bch|g
YYa Ybhk |gYa i |hd|W|cb"

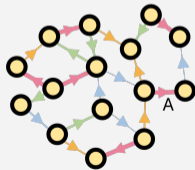
H Yd\UgYgUYi dXU|XYUW|ja Ygh|d.

—

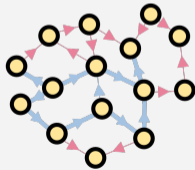
RS Algorithm – Synchrony

5gdfcdcgyXZ\h Ya cXY`YufbgUg[fci dgcZ]b_gVYWa YgnbWfcb]nYX'

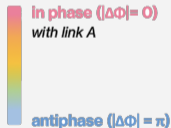
H\lgdfcj]XYgUdUh ZcfhY]bZcfa U]cbk ck h fci [\ h Ya cXY"KY
a YUgi fY]hk]h h YcfXYfdUfLa Yhf .



Initial, random phases, $R=0.20$

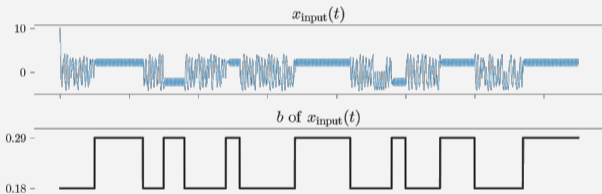


Learned phases, $R=0.75$



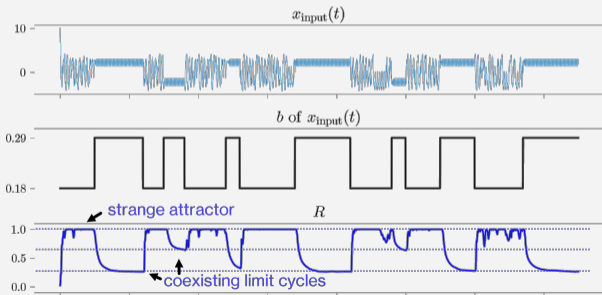
RS Algorithm – Reaction to Changing Dynamics

K \ Yb\h Y]bdi hXrbLa]MgWUb[YZh Ya cXY UXi ghgk \]WbcXYg
UfYgnbWfcb]nYXlc a UW"

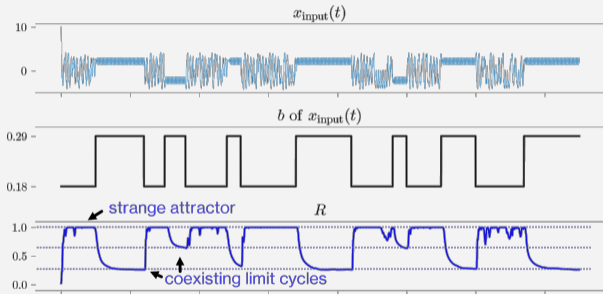


RS Algorithm – Reaction to Changing Dynamics

K \ Yb h Y] bdi hXrbLa]MgWUb[YZh Ya cXY UXi ghgk \]WbcXYg
UfYgnbWfcb]nYXlc a UW"



RS Algorithm – Reaction to Changing Dynamics



H |g|bgd|fYXi g|c UbUmYh YU[cf|h a gUdd]WV]hnc Ubca UmUbX
WbWdhXfZhXYhVM]cb''

RS Algorithm – Per-Input Synchrony

\rightarrow $hU^{\backslash}nk YVY]y YXh Uh^h [gWUb[]b[gnbWfcbnk UgYbci [\setminus hc XYhW^h$
 $WbWdhXfZi' < ck Yj Yf$ **it only captured large dynamical shifts,** bch
 $gi VhYWUb[Yg''$

$H YfYZcfYzk Y]blfcXi WXdyf!]bdi hgnbWfcbnk \setminus]Wcb^na YUgi fYg$
 $h YgnbWfcbncZ]b_gVbbYhXlc YUW]bdi hg bcXYg$

RS Algorithm – Per-Input Synchrony

It only captured large dynamical shifts, bch gi VhYWUbl Yg'

per-input synchrony generates rich features that amplify drifts, ja dfcj bl dYzfa UbWcZYhWjcbU[cf]ha g'

Concept Drift Detection

Concept Drift

H YWbWdhXfZhXhWjcbHg ZWgYgcbXhWjbl k \ Ybh Y
XlghfM hcbh UhUb jbdh hgXfUkbZca WUb[Yg'

hlgUbja dcfhUbhdfcVYa jba UWjbY`Yufjbl glbWa cgha cXYg
UfYVf]hhYlc jhUbXYj Yba jbcfXfZgfygi h]bkcfgYdYfZfa UbW'

KYi H]jnYh YUM]]mcZci fa cXYlc \] \] \ hXfZghe ja dfcj Yh Y
dYfZfa UbWcZ] YfYbhU[cf]ha gcbh fYYXUhgYg'

Concept Drift – Detectors

K YH Ygh YdYfZcfa UbWcZci fa cXY Udd]YXlc [YbYf]WcbWdh
XfZXYH WcbU[cf]h a g]bW X]b[.

5i lc YbWXYffYWbgfi Wcb a cXYgQQ

7i g]b[U[cf]h a g

AU]a i a a YubXgWYdUbWQQ

Concept Drift – Detectors

K YH Yghh YdYfZcfa UbWcZci fa cXY Udd]YXlc [YbYf]WcbWdh
XfZhXYH WjcbU[cf]h a gzbW X]b[.

5i lc YbWXYffYWbgfi Wjcb a cXYgQQ

7i gh]b[U[cf]h a g

AU]a i a a YubX]gWYdUbW]Q

5X]h]cbU`n]k YH YghGCH5zXU]gYhhi bYXXYH W]c]fg

BYi fU Gng]Ya =XYb] W]h]cbUbX6UhYg]Ub:]]h]b[fBG=6: LQ\$Q

6]X]fY W]h]cbU 8nb]a]WAcXY f68A LQ%Q

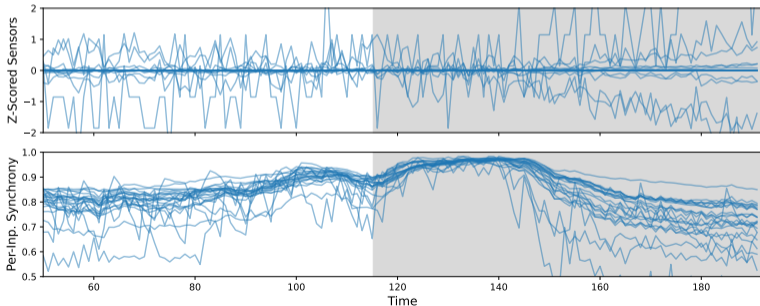
NASA C-MAPSS Dataset – Overview

H\YB5G5 7 A5DGGXUhgYh]bW XYgfYWfX]b[gZca gYbgcfg
cbUgYhcZg]a i `UHXh fVcZbYb[]bYgUgh YmVUghfcd\]W`m
XY[fUXY"

: c`ck]b[df]cfkcf_žkYWbglXf]hYUgh cZYUWfYWfX]b[
Uca Uci gO&Z%Q

NASA C-MAPSS Dataset – Per-Input Synchrony

DMF! jbdI hgnbWfcbnVM jbg **emphasizing the drifts before the cutoff**



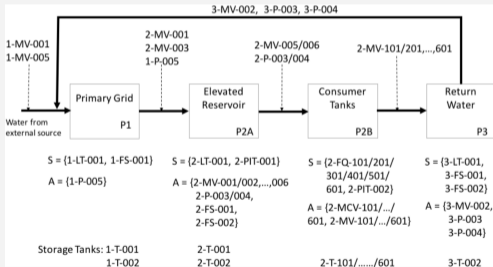
NASA C-MAPSS Dataset – Detector Performance

DFW elevates the performance of the generic models.

AYhcX	DFW	FYW	: %	8Y"
59 kJH FG	S') *% S'(*'	S'* & S'! (%	S') - ' S'* &%	%'), S'),
AA8 kJH FG	S'((% S'*) +	S'! - % 0.822	S'*%\$ S'+) \$	0.00 %) \$
7i gM]b[kJH FG	S'(% 0.860	%\$\$\$ S', S(S'),) 0.831	0.00 S'),

WaDI and SWAT Datasets – Overview

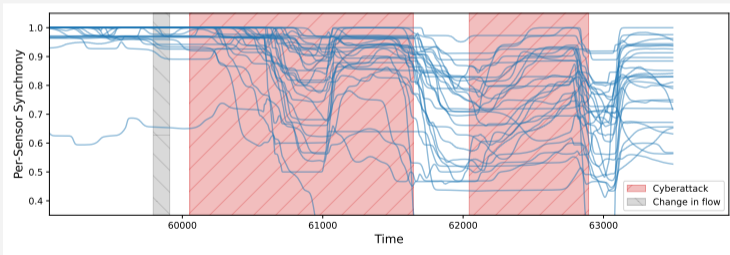
HY\[\ \] \hgcZci ffYgi `lgUfYcbh YGYWfYKUMfHYUa YbhHYghVYX
fGKUHfXUHghYhUbXkUMfXghfM hcbHYghVYXfK 58-fXUHghYhO%Z%Q



HYgYUfYWa d]WUfXUHghYhgcZfYU gYbgcYghUbXUWfUcYghfYU[h] kUMf

WaDI and SWAT Datasets – Per-Input Synchrony

DYf!]bdi hgnbWfcbmfYUMgk Vch fYU VwYfUHUWgUbXbcfa U XfZgž
g\ck]b[]gi gYZ `bYggVi hdcYbh]U`ndcgb[UdfcVYa ZcfXYHMcfg"



WaDI and SWAT Datasets – Simple Detectors

Ci fa Yh cXc`c[n]a dfcj YgdYfZcfa UbWcbh Yg]a d'Y] YbYf]W
 XYhWkfg

AYhcX	GKUH8UHgh			K58=8UHgh		
	DfYW]cb	FYW` : %GWfY	FYW` : %GWfY	DfYW]cb	FYW` : %GWfY	FYW` : %GWfY
59 <i>k]h FG</i>	S'S& S'S' ,	S'(- & 1.000	S'S) & S'S+'	S''S& S'%+	S'') S'* +'	S''& & S''& (
AA8 <i>k]h FG</i>	S'S(0.142	S'+(+ S'%&	S'S, (S'%)*	0.225 S''&]	S'S%& S'* %	S'S& S'' %
7i gh]b[<i>k]h FG</i>	S'S' - S'%-	S' - , S' (S	S'S+) 0.238	S'%)(S'%&	1.000 S'! * &	S''& , 0.321

WaDI and SWAT Datasets – SOTA Detectors

our method achieves SOTA results

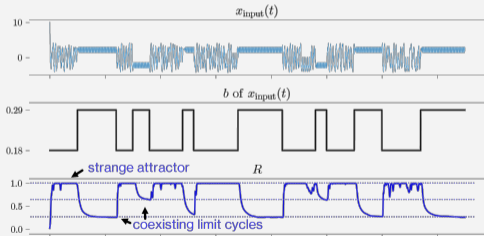
A Yh cX	GKUH8UHgh			K58-8UHgh		
	DfYWgcb	FYU	: %GWfY	DfYWgcb	FYU	: %GWfY
85; AA 0%Q	S")+	S" (')	S" +* -	0.904	S" %%	S" &&
I G58 0%Q	0.995	S" * &	S" ++%	S" & ')	S" (* &	S" %
68A 0%Q <i>kjh FG</i>	S" - % S" +&	S" * ,) S" * ' %	S" , %% S" +*)	S" & +* S" % \$	S") - ' S")) +	S" ++ S" &&
BG-6: 0%Q <i>kjh FG</i>	S" , - & S" (')	S" +%& 0.810	S" + & 0.871	S" & (S") +(S" (- * 0.876	S" % 0.694

DM!j bdi hgnbWfcbnlgUck!Xa YbgjcbU XnbLa jW fydfYgMbHjcbh Uha UWYgh YUggi a dhjcbczbi fu ghUM!gdUW a cXYg]_YBG-6: Vi hbchh YfYWbgfi Wjcb!VgXX68A "

Controlled Dynamics Using Synchrony

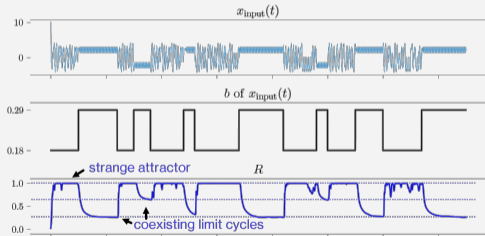
Controlled Dynamics – Training an RS Network

5gkYg\ckYXZfUbb[hYf\nh a Mg\Uf]b[bYkcf_i g]b[]bdi h
k]h a i]hdYXnbLa Mg`YUXglc X] YfYbhgrbWfcbnjUi Yg



Controlled Dynamics – Training an RS Network

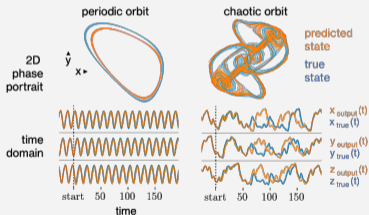
5gk Yg\ck YXZfUj]b[h Yf\nh a]g\Uf]b[bYtkcf_ i g]b[]bdi h
k]h a i]hd YXnb]a]g\YUXg]c X] YfYbhgrbWfcbnj Ui Yg



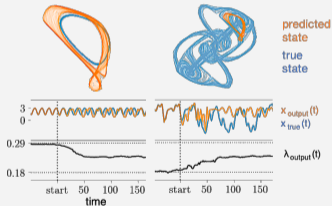
6i hk \Uh\UddYbgk \Ybk YdfYX]M]Z h fYXnb]a]g]k]h h]gbYtkcf_3

Controlled Dynamics – Prediction of Different Dynamics

< YfYzk Yg\ck h YfYgi lgcZdfYX]M]b[Z h fYXrbUa]MgUZFVY]b[hfUjYXcbVch XrbUa]Mg

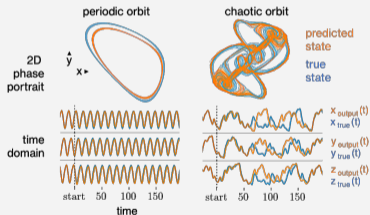


Standard RC

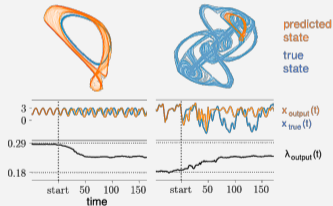


Controlled Dynamics – Prediction of Different Dynamics

< YfYzk Yg\ck h YfYgi lgcZdfYX]M]b[Z h fYXrbLa]MgUZFVY]b[hfUjYXcbVch XrbLa]Mg



Standard RC



Rhythmic sharing is able to reproduce both, k \]YU[YbY]WØGB VØUHYgU
 Wa V]bU]cbcZh Y]kc"

Controlled Dynamics – Synchrony Freezing

? bck]b[h]gžWbk YV/bfc`k \]W XnbLa]gk YfYdfcXi W3

Controlled Dynamics – Synchrony Freezing

? bck]b[h lgzWbk YVbfc`k \]W XnbLa]Ngk YfYdfcXi W3

Yes! KYWbZYnYh YgnbWfcbnLbX]bfcXi WUbyk j Uf]UVYz
hYa YUbd\UgY "

6ngY]b[hYa YUbd\UgYzk Y`cW_h YbYkcf_]bUghU]W
Wb [i fU]cb"

Controlled Dynamics – Mean Phase

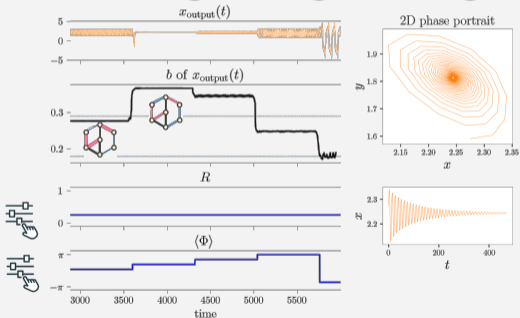
9UWghUWcb [i fUjcbdfYX]MgUX] YfYbhgYhcZXnbUa]Mg'

Controlled Dynamics – Mean Phase

9UWghUWcb [i fUjcbdfYX]MgUX] YfYbhgYhcZXnbUa]Mg'

Controlled Dynamics – Mean Phase

9UWgHjVWb [i fUhc bdfYX]MgUX] YfYbhgYhcZXnbUa]Mg'



Controlled Dynamics – Mean Phase

9UWghUWcb [i fUjcbdfYX]MgUX] YfYbhgYhcZXnbUa]Mg'

Controlled Dynamics – Mean Phase

9UWgHjWcb [i fUjcbdfYXjMgUX] YfYbhgYhcZXnbUa jMg'

F\nh a jMg\Uf]b[gcgW/Ujcbga U_Y]h **equivalent to many different ESNs!**

Conclusions

Contributions

Cj Yf k c k c f _ g ž k Y \ U j Y \ [\ ` [\ h X U b Y k f Y g Y f j c] f W a d i h b [d U f U X [a ž \ n h a] W g \ U f] b [ž U b X] g U d d ` M U M] h n k c h Y V b W d h X f] z h X h M] c b h U g . "

Contributions

Cj YfIkckcf_gžkY\UjY\[\ \]\ \hXUbYk fYgYfj c]fW@a di Hb[
dUfUX[a ž\ñh a]Wg\Uf]b[žUbX]lgUdd`[VV]]hmk h YVebWdhXf]Zh
XhV]cbHg_ "

H]gU[cf]h a]gUW'a]bU]cbcZci fbcj Y i bXfghUbX]b[cZUgfcVh]Yg
UgVeb]fc `YfgcZbYi fcbUW[b]hcb"

Contributions

Cj Yf hkc kcf_gžk Y\Uj Y\[\ \] \hXUbyk fYgYfj c]fWā di h]b[
dUfU\] a ž\ñā a]Wg\Uf]b[žUbX]lgUdd]WU\]]hñc h YVebWdhXf]Zh
XhW]cbhUg."

H]gU[cf]hā]gUWā]bU]cbcZci fbcj Yi bXfghUbX]b[cZUghfcWñhYg
UgVeb]fc`YfgcZbYi fcbUW[b]hcb"

H YU[cf]hā]a dYa Yb]ghkc \ñch\ YgYgcZUghfcWñhYg fc`Y]b
Yuf]b[.

@Yuf]b[]bjc] Ygf\ñā a]WUf]U]cbg]b`]b_gfYb[h žUbXž

@Yuf]b[cWf]gj]UVcfX]bU]cbcZh Yd\ UgYgcZh YgYf\ñā a]W
j Uf]U]cbg"

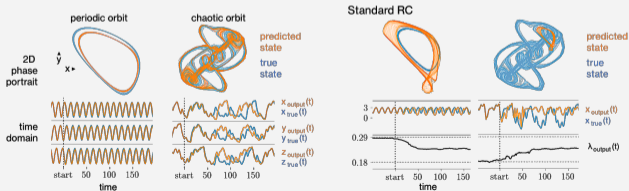
Contributions

H YfYgi 'Hb[U[cf]h a 'YufbgXYgd]hZubXXYhWgZwUb[Yg]bh Y
]bdi hXUu'

Contributions

\mathbb{R}^n dynamics $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x})$ $\mathbf{x}(0) = \mathbf{x}_0$ $\mathbf{x}(t) = \mathbf{x}_0 + \int_0^t \mathbf{f}(\mathbf{x}(s)) ds$ $\mathbf{x}(t) = \mathbf{x}_0 + \mathbf{A}t + \mathbf{B}t^2 + \dots$

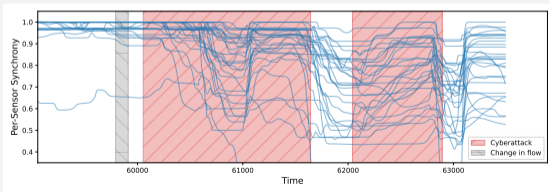
$\mathbf{x}(t) = \mathbf{x}_0 + \mathbf{A}t + \mathbf{B}t^2 + \dots$ **rhythmic sharing retains both** $\mathbf{x}(t) = \mathbf{x}_0 + \mathbf{A}t + \mathbf{B}t^2 + \dots$



Contributions

Highly accurate detection of cyberattacks and changes in flow.

Significantly improve the ability of downstream concept drift detectors.



Future Work – Algorithmic Development

KYd`Ubhc Wbhb| Ykcf_ |b| cbi bXYfghUbX|b| h Yf\nh a]W
g\Uf|b| U| cf|h a "GdYV\W`nřk YkUbhc ZcWgcb

\ck \mYfdUfUa Yhf gY`W|cb WUb| YgdYfZcfa UbWk\Yb
Yl hfUdc`U|b| cfXYhW|b| X|Zgž

\ck kYVWbdYfZcfa X|ZhXYhW|cb]ba cfYVWa d`Yl
Ybj]fcba YblgžUbXž

\ck kYVWbUdd`nci fUM]hmc`YUfba i`hd`YgYlgcZ`nbUa]V|c
fYU!kcfXXUhgYlg'

Future Work – Biology Experiments

5XX]hcbU`nzk Yk Ubhc i bXYfghUbX]Zh Ya cXY WUb[Yg\ck kY
h]b_ Uvci hh YVfUj"Gca Y]bhYfYgh]b[WbbYV]cbggi [[YghYX
Vnh YU[cf]ha UfY.

h Yfc YcZLghfcVhYgXi f]b[Ybj]fcba YblU cf gYbgcfmWUb[Yž

]ZLghfcVhYgnbWfcb]nU]hcbUhYfgbYi fcbU Wa di hU]cbžUbXž

k\Yh Yfci fU[cf]ha gUv]hYga Udhc]b;j]fc bYi fcbU fYgYfj c]f'

Acknowledgements and Questions

How many of you have used the following tools?
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DYUgYfYUWci hlc Yufba cfY

UbK\]h\ci gY. ianjw@umd.edu

KcZ Ub[@cgYfhwlosert@umd.edu

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F\nh a]G\Uf]b[5[cf]h a ž &&& ž]bfYj]kE'

References – I

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HybXgbBYi fcgVjWgž c"&&čd'&&, &%žAUr%- - "

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Ybj|fca YbUgYgb| Vnř|a UfncXybUfjcVhYgž 5Y'6c'fkY|b\ žj c"+žd'Y&&&&&- ž-i bY&&& "

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References – II

M? i fUa clečZ\ Ya MWcgWUjcbgžkU YgžUbXh fV YbW

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9"Kc ZbXHK]bXgWž 5 a YhcXlc VbWa Uf_ \] \!Xja Ybg]cbU dfcWggXfZbXhM]cbž >"-bY"A Ubi Z5d" &S& "

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7": Yb[UbXD'H]Už Hja YgM]YgUba UnKXhW]cbZcfWwYf:d\ng]W]gng]Ya gj]ubYi fUgng]Ya]Xb] W]cb UbXVUn]g]Ub]hf]b[ž]bDfcWYX]b[gcZ]h Y&+h 57A Gž ?88 7cbZfYbW]cb?bck YX] Y8]gW] Yfina 8UU A]b]b[ž? 88 &žBYk Mf_žBM] G5žd'&), & *+ž5ggcV]U]cbZcf7ca di H]b[AUW]bYfina&S&%

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5"5"6UU]bY ž5"AU]U]ZbX8"? U ž 5i lc YbW]XfVugYXgYa]!gi dYf]]gYXUba UnKXhW]cb]bli fVcZb Yb[]bYgž -bYfU]cbU>ci fbUcZ5X] UbWX7ca di HfGM]YbW]UbX5dd]M]cbgž c "%žbc"%ž&S&S& "

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; "Ni ž@"<i Ub[žS"@žbX@"; cb[ž5bca UnXWw]cbZfa i Hj U]UYHja YggM]YgXUcZUfc!Yb[]bYVgYX
cbXYd`ga U lcYbWXMž]b 88& *h -bHfbU]cbU 7cbZfYbWcb9YMc]MgUbX7ca a i b]M]cbžBYkcf_
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>"; c\žG"5XYdi ž" B">i bYcžbX5" AUhi ž 5 XUHgYhc gj ddcfhYgYUW]bh YXYg[bcZgYWFYkUMF
HfYUa Ybhng]Ya gž]b 7f]W -bZfa U]cb-bZUgfi Wi fYgGYWf]mf " < Uj UbYUbi žF"GYlc Už< "BÜggcdci `cgž
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6"Ncb[žE"Gcb[žA"F"A]bžK"7\ Yb[ž7"@ a YrUbi ž8"7\ cžbX<"7\ Ybž 8YYdU lcYbWXB] [U gg]Uba] li fy
a cXYZfi bgj dYf] gYXUca UnXWw]cbž]b -bHfbU]cbU 7cbZfYbWcb@Yub]b[FYdYgYbU]cbgž88%"

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