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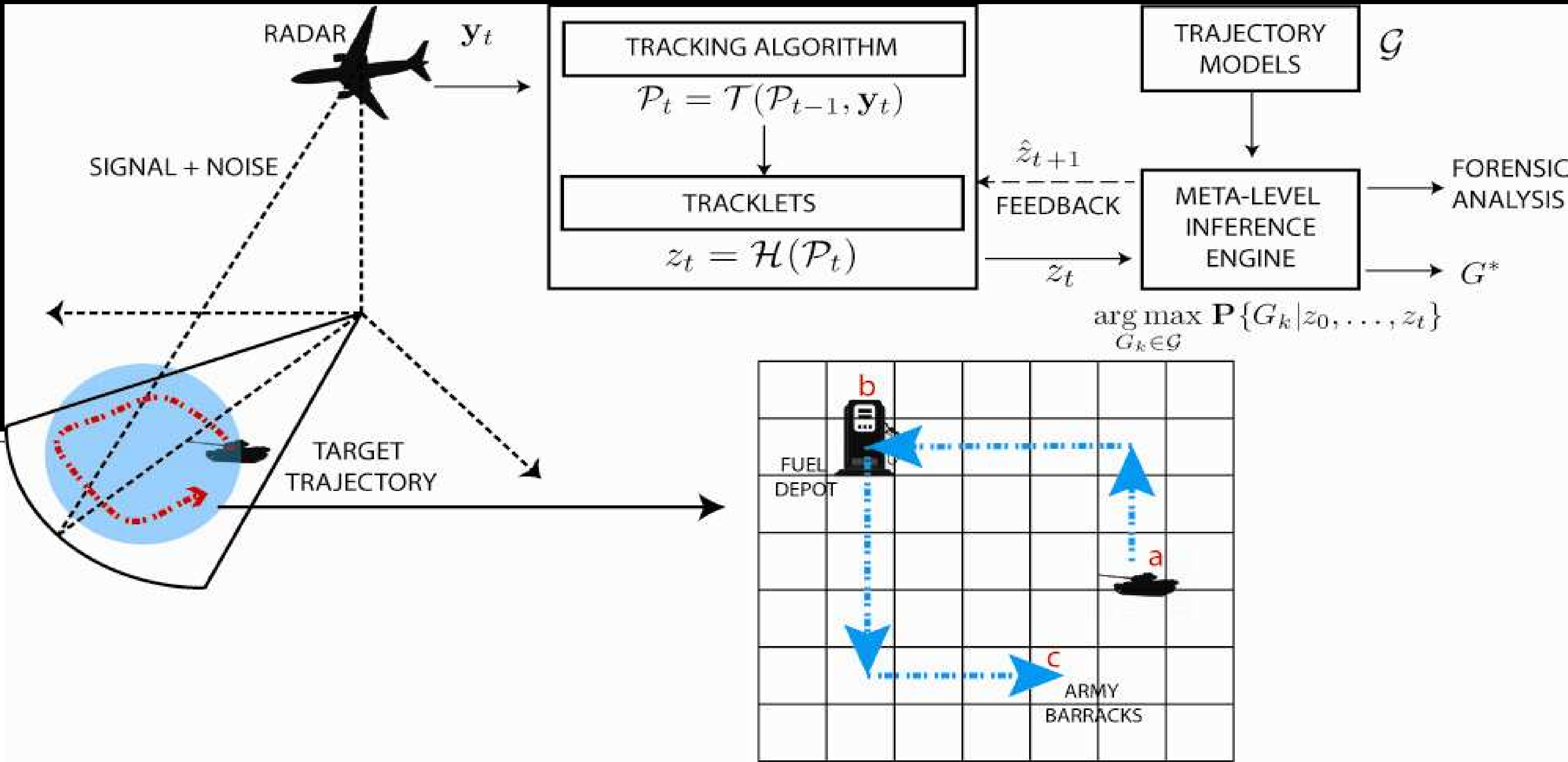
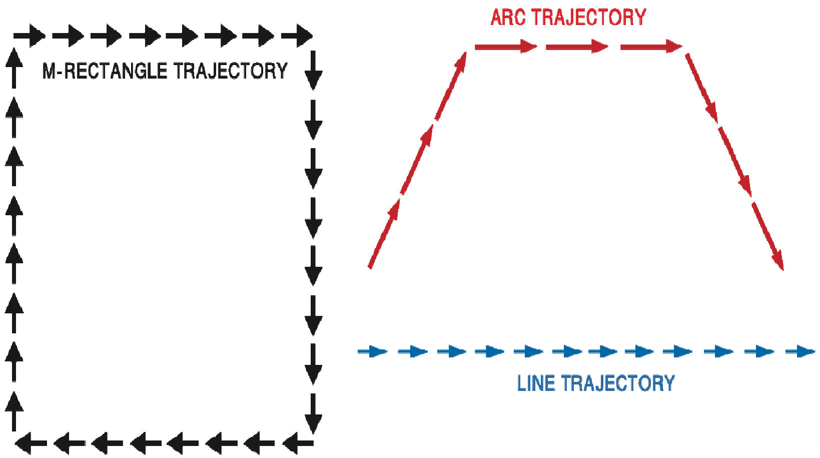
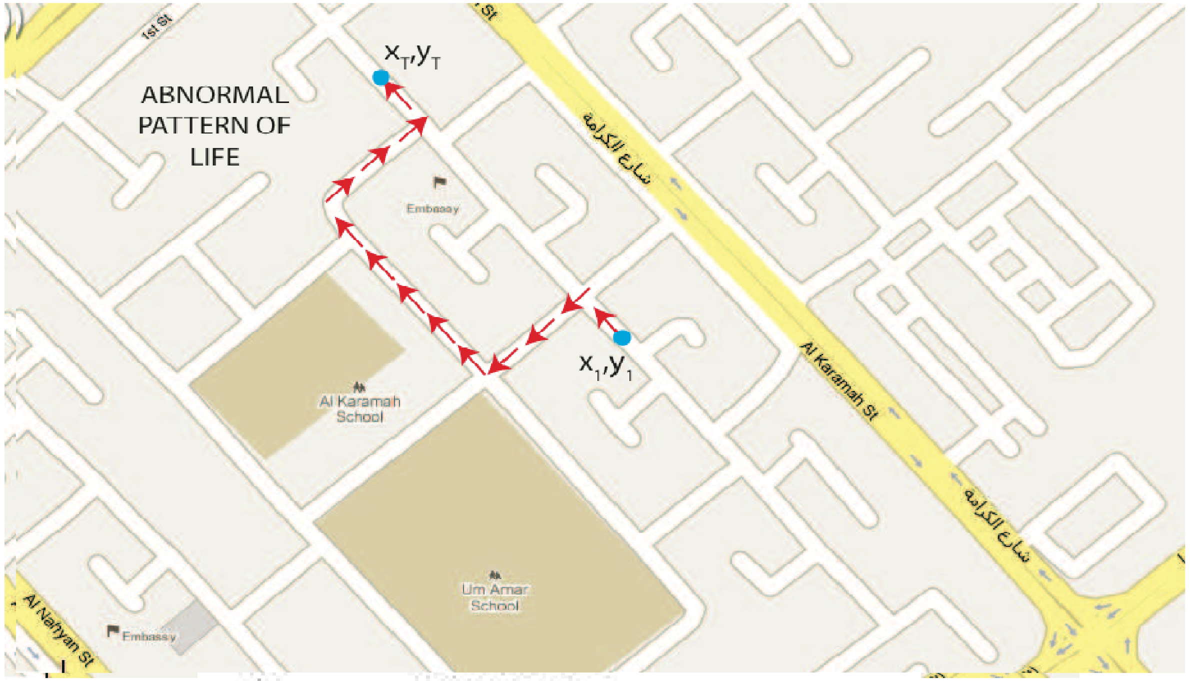
Destination Aware Target Tracking via Syntactic Signal Processing



Syntactic patterns for Intent Inference

Ex1: Abnormal Pattern of Life

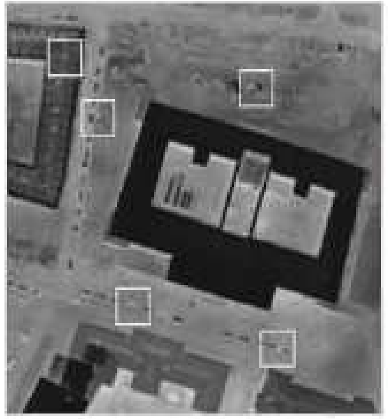


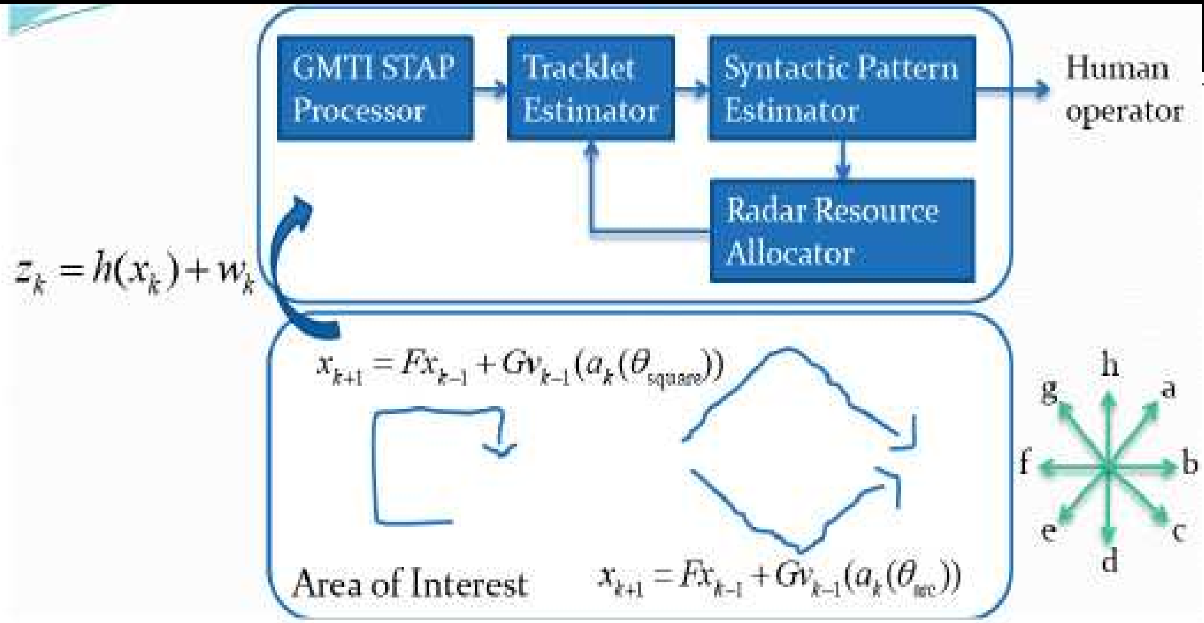


Ex2: Destination Constrained Trajectories

State-Space Models for target movement are for short time scales. How to model these longer time-scale trajectories? How to do Bayesian estimation?

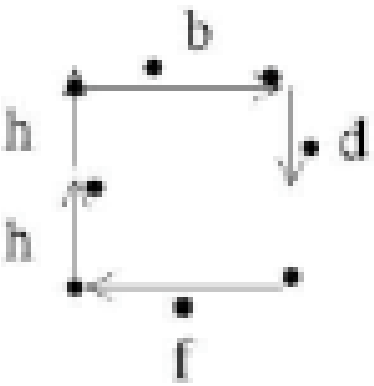
Main Idea: Parsimonious Models



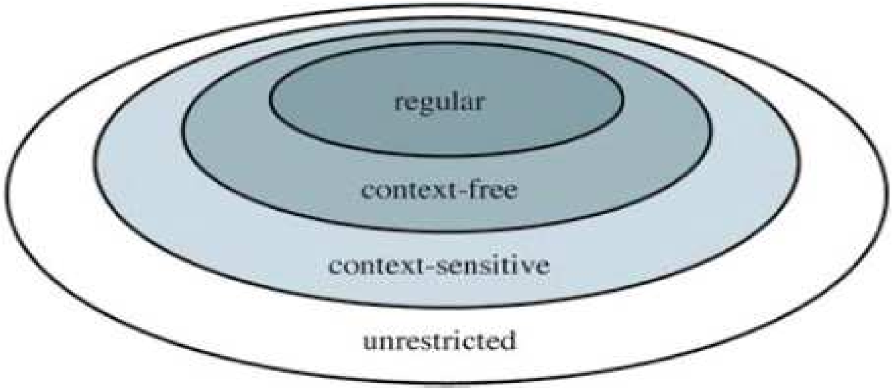


Green Zone Protection

- How to assist human operators in intent inference? Meta-level signal processing human-sensor interface (beyond physical sensor)
- Key Paradigm: (i) Stochastic Context-Free Grammar Model
  (ii) Reciprocal Markov Processes (1-dimensional Markov random fields).

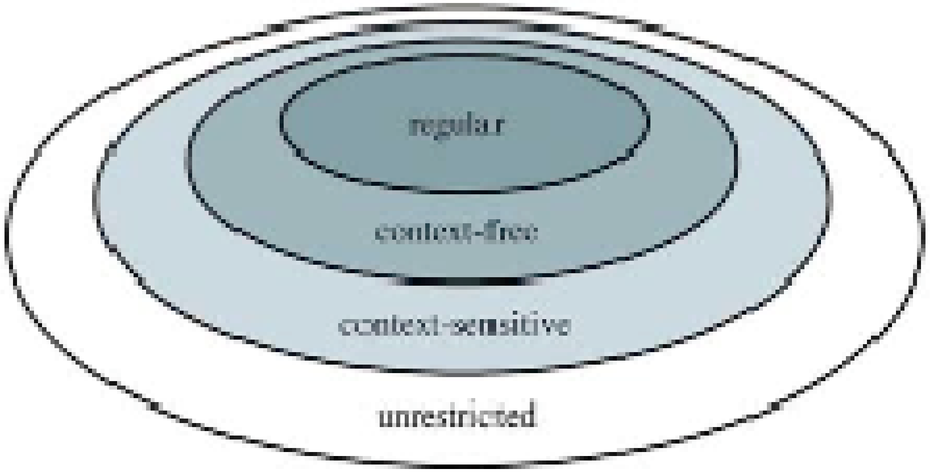


Chomsky Hierarchy of Formal Languages



SCFG – Advantages

- Convenient model to capture domain knowledge of human operator
- Polynomial complexity Bayesian algorithms for estimating trajectory type (originating from Bioinformatics, Durbin, Eddy, Biological Sequence Analysis, 1998.
- Scale-invariance and Rotation-invariance (Robust)
- Efficient model (in terms of entropy) since finite state automata are a subset of context-free grammars

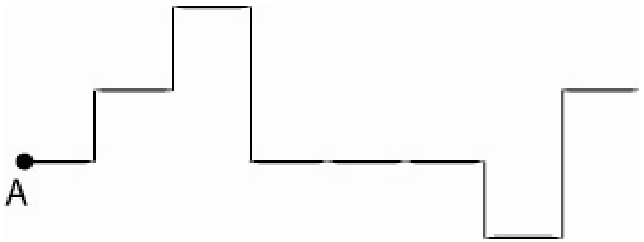


Begin if
....
...
...
End if

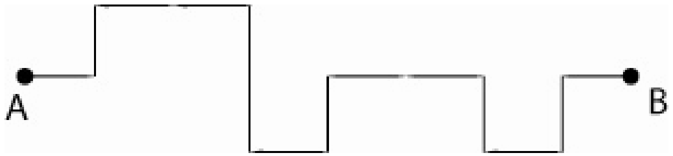
Trajectory Modeling – beyond Markoviana

Example 1:

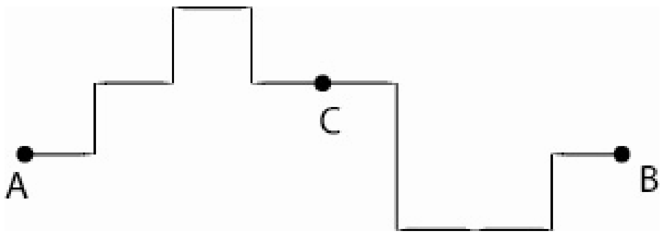
1. Random Walk



1. Markovian Bridge (goal-directed trajectory) = reciprocal process

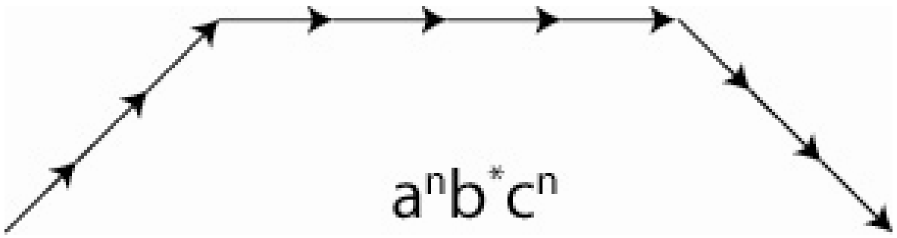


2. SCFG (allows random time between waypoints)

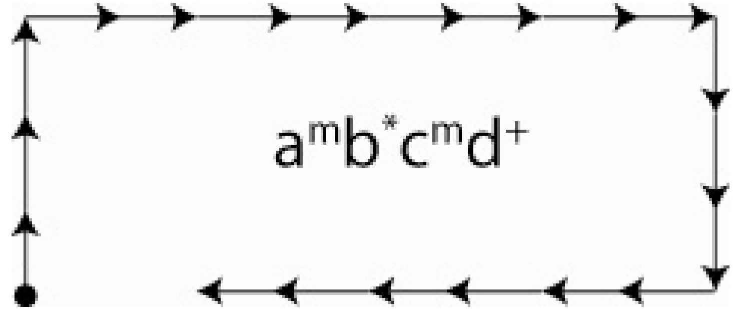


Example 2 (cannot be modeled by an HMM):

1. Arc Trajectory



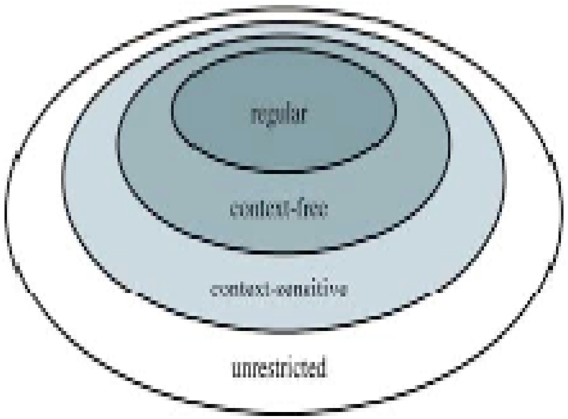
2. m-Rectangle Trajectory



SCFG vs HMM

HMM (stochastic regular grammar or automata):

$$A = \begin{bmatrix} & S_1 & S_2 \\ S_1 & 0.9 & 0.1 \\ S_2 & 0.2 & 0.8 \end{bmatrix}, \; B = \begin{bmatrix} & a & b \\ S_1 & 0.6 & 0.4 \\ S_2 & 0.3 & 0.7 \end{bmatrix}$$



Non terminals $= NT = \{\text{start}, S_1, S_2\}$,

Terminals $= T = \{a, b, \text{end}\}$. Production rules P:

$S_1 \overset{0.54}{\rightarrow} aS_1,\ S_1 \overset{0.03}{\rightarrow} aS_2,\ S_1 \overset{0.36}{\rightarrow} bS_1,\ S_1 \overset{0.07}{\rightarrow} bS_2$

$S_2 \overset{0.12}{\rightarrow} aS_1,\ S_2 \overset{0.24}{\rightarrow} aS_2,\ S_2 \overset{0.08}{\rightarrow} bS_1,\ S_2 \overset{0.56}{\rightarrow} bS_2$

HMM strings grow linearly from left to right.

Example: $S_1 \implies aS_2 \implies aaS_1 \implies aabS_1$

SCFG vs HMM

Stochastic Context Free grammar: (NT, T, P) with

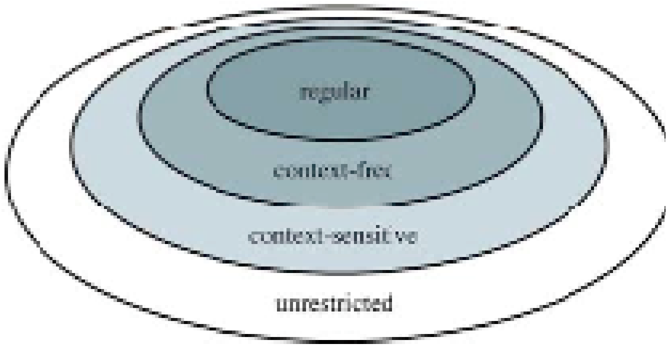
$$S_1 \overset{0.54}{\rightarrow} aS_1,\ S_1 \overset{0.03}{\rightarrow} aS_2,\ S_1 \overset{0.36}{\rightarrow} bS_1,\ S_1 \overset{0.07}{\rightarrow} bS_2$$

$$S_2 \overset{0.12}{\rightarrow} aS_1,\ S_2 \overset{0.24}{\rightarrow} aS_2,\ S_2 \overset{0.08}{\rightarrow} bS_1,\ S_2 \overset{0.3}{\rightarrow} bS_2,$$

$$\boxed{S_2 \overset{0.26}{\rightarrow} aS_2S_1}$$ CFG strings grow inside out or on a tree

Example:

$$S_1 \Longrightarrow aS_2 \Longrightarrow aS_2S_1 \Longrightarrow aS_2aS_1 \Longrightarrow aaS_2S_1abS_2$$



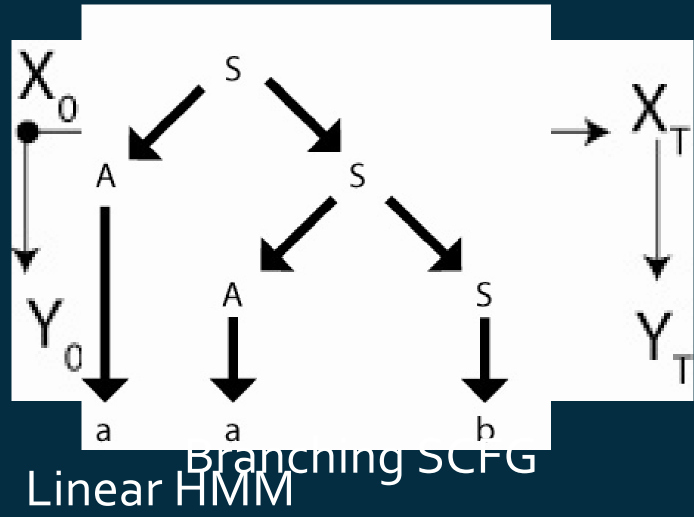
Remarks:

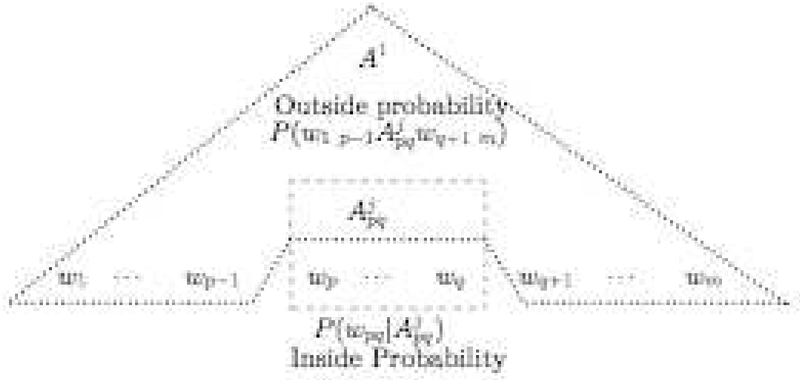
1. SCFGs are Multi-type Galton Watson Branching processes where the order matters – each realization is a tree (Directed acyclic graph).
2. Realization Theory: Chomsky normal form, etc
3. Pumping Lemmas – to prove if a grammar does not belong to a particular class

SCFG – Signal Processing Algorithms

Syntactic Signal Processing: Given data string (also called sequence of terminals) $Y_T = (y_1, \ldots, y_T)$ x denotes state, N denotes non-terminal.

	HMM	SCFG
Forward Filter	$P(x_k, Y_{1:k})$	$P(N_{k_1:k_2}, Y_{1:k-1}, Y_{k+1:T})$
Backward Filter	$P(Y_{k+1:T} \mid x_k)$	$P(Y_{k_1:k_2} N\mid_{k_1:k_2})$
MAP	Viterbi	Earley Stolcke Parser or Cocke-Younger-Kasami
EM alg	Forward/backward	Inside Outside





SCFG Bayesian estimation is polynomial complexity – cubic in data length.

An Arc Trajectory ($a^n b^+ c^n$)

VELOCITY TRACKLETS

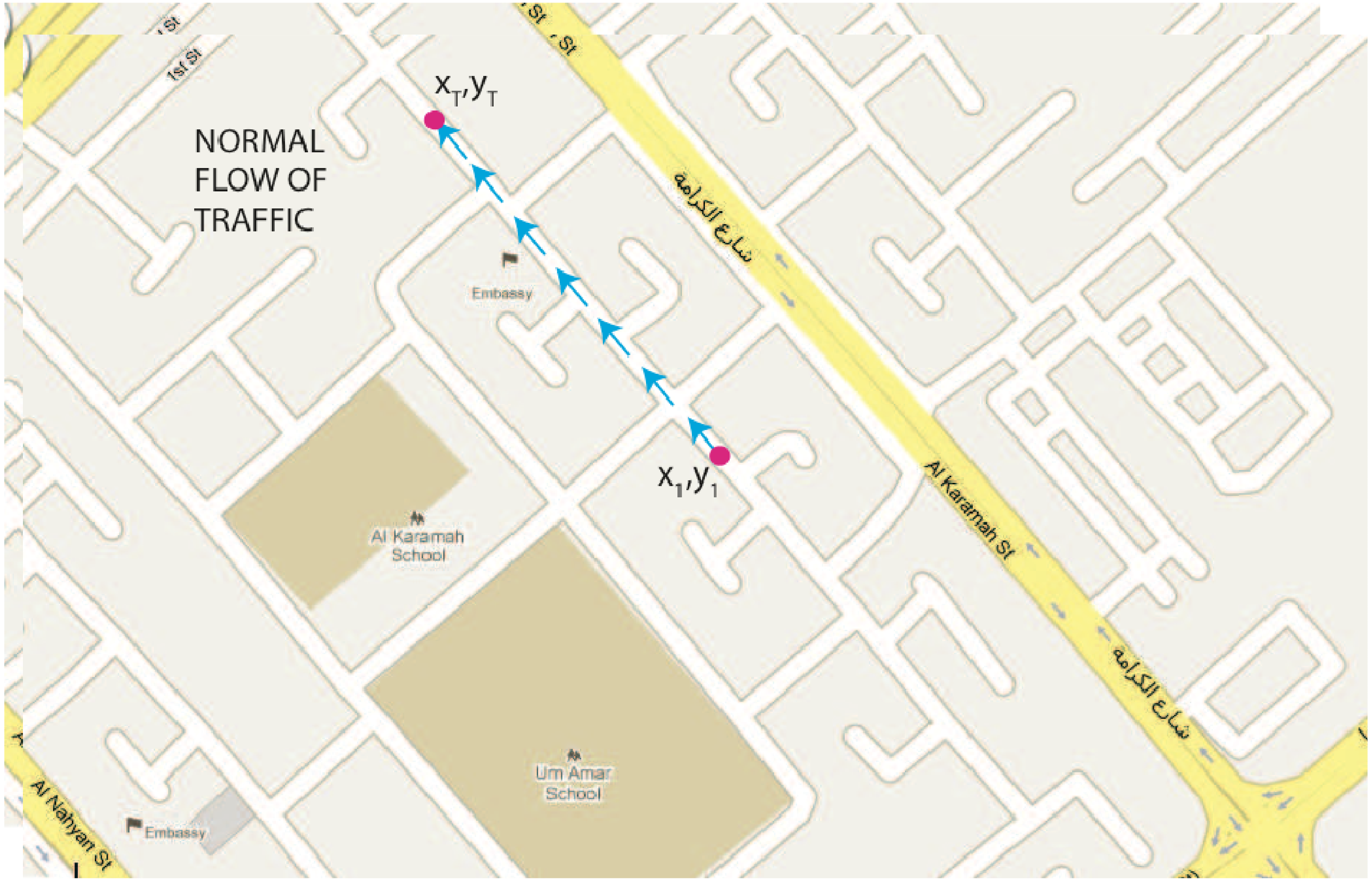
S -> A X C

S -> A B C-> $\frac{3\pi}{4}$ B C

-> $\frac{3\pi}{4}$ π B C

-> $\frac{3\pi}{4}$ π π C

-> $\frac{3\pi}{4}$ π π $\frac{5\pi}{4}$



GRAMMAR RULES

S -> A X C

X -> A X C | A B C | B

A -> $\frac{3\pi}{4}$

B -> π B | π

C -> $\frac{5\pi}{4}$

Summary and References

1. Syntactic Models allow for complex trajectories – work seamlessly with legacy trackers.
2. Polynomial complexity Bayesian stochastic parsing (filtering) algorithms
3. Human—sensor interface – SCFG parsing assists human in intent inference.
4. System-theoretic issues: Sub-criticality (polynomial stability); Constraints.
5. Sensitivity of posterior distribution to prior.

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3. K.S. Fu, *Syntactic Pattern Recognition*, Prentice Hall, 1982.
4. Wang, Krishnamurthy, Balaji, *Syntactic Tracking and Intent Inference for GMTI*, IEEE Trans Aerospace Electronic Systems, Jan 2012.
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6. Visnevski, Krishnamurthy, Haykin, *Syntactic Modeling of Multifunction Radars*, Proceedings of IEEE, 2007.