Cognitive Green Communications: From Concept to Practice

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Outline

- Part I – the Concept: Energy-efficient Cognitive Green Radio Communications
- Part II – the Practice: Cognitive Green Communications for Achieving Energy Saving within Cellular Mobile Networks

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UEB - Université Européenne de Bretagne & Supélec
Global Warming – The Most Dangerous Threat?
Terrible Climate Change: Trans-Arctic Shipping Routes Navigable 21st-midcentury

Data Explosion - Exponential Traffic Growth

- Total Backbone
- Internet Video
- P2P
- Wireless Data
- Wireless Voice

Traffic (Tb/s)

Year

2010 2015 2020

3,600,000

1,800,000

108% CAGR 2009-2014

Source: Cisco VNI Mobile, 2010
Data Explosion - Exponential Traffic Growth (2)

What Happens in an Internet Minute?

- 639,800 GB of global IP data transferred
- 20 New victims of identity theft
- 204 million Emails sent
- 47,000 App downloads
- 583,000 In sales
- 61,141 Hours of music
- 20 million Photo views
- 3,000 Photo uploads
- 320+ New Twitter accounts
- 100,000 New tweets
- 135 Botnet infections
- 1,300 New mobile users
- 100+ New LinkedIn accounts
- 277,000 Logins
- 6 million Facebook views
- 2+ million Search queries
- 30 Hours of video uploaded
- 1.3 million Video views

And Future Growth is Staggering

Today, the number of networked devices = the global population
By 2015, the number of networked devices = 2x the global population
In 2015, it would take you 5 years to view all video crossing IP networks each second

Part I: Green Communications

Paradigm Change from Coverage- & Capacity-Driven to Energy-Efficiency Driven Era

Network Cost (Energy Consumption by Existing Technologies)

Traffic Volume

Energy Consumption by Green Technologies

Time (Year)

Coverage Dominated
Capacity Dominated
Energy Efficiency Dominated

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Supélec
Energy Crisis and Challenges

Prediction of power consumption by information network systems

Electric Power Consumption

- CO2: 130M ton (240BkWh)
- 20% of total power consumption in Japan (26M ton = 8 million cars, 50BkWh)
- CO2: 300Mton (550BkWh)

2050

Current Technology

High energy reduction is needed based on technical innovations.

Source: Prof. T. Aoyama, Keio University, ISCIT 2010 Keynote Speech.
## ICT Sector Commitments to Targets and Deadlines for CO$_2$ and Greenhouse Gas Emissions and Energy Efficiency/Consumption (European Commission 2009/03/12)

<table>
<thead>
<tr>
<th>Companies</th>
<th>Target reduction %</th>
<th>Baseline *</th>
<th>Target date</th>
<th>Comment</th>
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<tbody>
<tr>
<td>Alcatel–Lucent</td>
<td>10</td>
<td>2007</td>
<td>2010</td>
<td>CO$_2$ emissions of facilities</td>
</tr>
<tr>
<td>Bell Canada</td>
<td>15</td>
<td>Not given</td>
<td>2012</td>
<td>GHG emissions</td>
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<tr>
<td>British Tele-Communications Plc</td>
<td>80</td>
<td>1996</td>
<td>2020</td>
<td>CO$_2$ emissions</td>
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<tr>
<td>Cisco Systems</td>
<td>25</td>
<td>2007</td>
<td>2012</td>
<td>GHG emissions</td>
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<tr>
<td>Dell</td>
<td>Additional 15</td>
<td>Not given</td>
<td>2012</td>
<td>Operational carbon intensity</td>
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<tr>
<td>Deutsche Telekom AG</td>
<td>20</td>
<td>2006</td>
<td>2020</td>
<td>CO$_2$ emissions</td>
</tr>
<tr>
<td>Ericsson</td>
<td>15 - 20</td>
<td>2006</td>
<td>2008</td>
<td>Energy efficiency</td>
</tr>
<tr>
<td>France Telecom</td>
<td>20</td>
<td>2006</td>
<td>2020</td>
<td>CO$_2$ emissions</td>
</tr>
<tr>
<td>Hewlett-Packard</td>
<td>16 - 40</td>
<td>2005</td>
<td>2010-2011</td>
<td>Energy consumption and GHG emissions for operations and products</td>
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### Energy Crisis and Challenges (3)

**ICT Sector Commitments to Targets and Deadlines for CO₂ and Greenhouse Gas Emissions and Energy Efficiency/Consumption (European Commission 2009/03/12)**

<table>
<thead>
<tr>
<th>Company</th>
<th>Percent</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Emission Type</th>
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<tbody>
<tr>
<td>Intel</td>
<td>20</td>
<td>2007</td>
<td>2012</td>
<td>Carbon footprint</td>
<td></td>
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<tr>
<td></td>
<td>30</td>
<td>2004</td>
<td>2010</td>
<td>GHG emissions</td>
<td></td>
</tr>
<tr>
<td>Motorola</td>
<td>6</td>
<td>2000</td>
<td>2010</td>
<td>CO₂ emissions</td>
<td></td>
</tr>
<tr>
<td>Nokia</td>
<td>6</td>
<td>2006</td>
<td>2012</td>
<td>Energy consumption of offices and sites</td>
<td></td>
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<tr>
<td>Nokia Siemens Networks</td>
<td>20 - 49</td>
<td>2007</td>
<td>2009-2010</td>
<td>Energy consumption of products</td>
<td></td>
</tr>
<tr>
<td>Sun Microsystems Inc.</td>
<td>20</td>
<td>2007</td>
<td>2015</td>
<td>GHG emissions</td>
<td></td>
</tr>
<tr>
<td>Telecom Italia</td>
<td>30 % increase</td>
<td>2007</td>
<td>2008</td>
<td>Eco-efficiency indicator</td>
<td></td>
</tr>
<tr>
<td>Vodafone Plc</td>
<td>50</td>
<td>2006/2007</td>
<td>2020</td>
<td>CO₂ emissions</td>
<td></td>
</tr>
<tr>
<td>European Union (all sectors)</td>
<td>20</td>
<td>1990</td>
<td>2020</td>
<td>CO₂ emissions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Projected energy use in 2020</td>
<td>2020</td>
<td>Energy savings/efficiency</td>
<td></td>
</tr>
</tbody>
</table>
Architecture of Telecommunication Networks
Energy consumption composition in Vodafone (Source: Vodafone)
Energy Consumption in Radio Access Networks

- Mobile Stations: 10%
- Mobile Network: 20%
- Base Stations: 80%
- Network: 90%

Mobile Terminals
Energy Consumption Reference Model for Base Station

Examples of power consumption values of RBS (Unit: Watt)

<table>
<thead>
<tr>
<th></th>
<th>Input</th>
<th>PS</th>
<th>TXM</th>
<th>RBS</th>
<th>CC</th>
<th>Output</th>
<th>EE</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM</td>
<td>3802</td>
<td>600</td>
<td>300</td>
<td>2400</td>
<td>500</td>
<td>120</td>
<td>3.1%</td>
</tr>
<tr>
<td>3G</td>
<td>300</td>
<td>20</td>
<td>20</td>
<td>150</td>
<td>110</td>
<td>60</td>
<td>20%</td>
</tr>
</tbody>
</table>

Energy Consumption Reference Model for Base Station (2)

Note: Values in italic are power consumption figures in GSM system.
Increasing bandwidth can also save energy, depending on context.

Cognitive Green Communications
Intelligence with Adaptation, Balancing & Optimization for Network Energy Saving

Basics of Cognitive Radio

- Cognitive Radio & Networking
  - Input - Decision Making - Action
    - Environment awareness (Input)
      - External stimuli
      - Sensing
    - Interpretation & Learning (Decision Making)
      - Reasoning
      - Interpretation
      - Learning
    - Implementation of Decision (Action)
      - Actuation
      - Parameter change

- Sensing the radio context, service context, location context and user context
- Interpreting the radio environment
- Reacting to the changes (radio protocols), tuning the radio and implementation parameters, fault management
Features & Key Functionalities of Cognitive Radio (Cognitive Cycle)

Embedded Intelligence in a General Cognitive Radio Transceiver

Cognitive Radio Node

Protocol Stack

Application Layer
Network Layer
MAC Layer
PHY Layer

Control Unit

Context Engine
Role Manager

Cognition Engine
Trust and Security Module

Config Manager
Policy Manager

To other control units

Source:

Why Reinforcement Learning?

Machine Learning

- Supervised Learning
- Unsupervised Learning
- Reinforcement Learning

Why statistical?
Noise, uncertainty, large data sets, … Proven to be effective!
Basics of Reinforcement Learning

- **Policy**: What to do
- **Reward**: What is good
- **Value**: What is good because it predicts reward
- **Model**: What follows what
Markov Decision Processes (MDPs)

In Reinforcement Learning, the environment is modeled as an MDP, defined by

- $S$ – set of states of the environment
- $A(s)$ – set of actions possible in state $s \in S$
- $P(s, s', a)$ – probability of transition from $s$ to $s'$ given $a$
- $R(s, s', a)$ – expected reward on transition $s$ to $s'$ given $a$
- $\gamma$ – discount rate for delayed reward

Discrete time, $t = 0, 1, 2, \ldots$
Workflow of Energy Saving Mechanism Enabled by Cognitive Process/Cycle

Once upon a Time – What was Cognitive Radio, Really?

Joe Mitola’s Cognitive Radio (1999)

DySPAN’s Cognitive Radio (2007)

Simon Haykin’s Cognitive Radio (2005)

Cognitive Radio (G. Gur and F. Alagoz, 2011)
Once upon a Time – What was Cognitive Radio, Really? (2)
Part II: The Practice – Energy Saving for Greener Cellular Mobile Networks

“Tidal Effect” of Cellular Networks’ Traffic Flow & Loads
Representative Patterns of Traffic Loads during One Day (Cellular Networks)
Normalized load of three different cell sectors over 3 weeks. The moving average of each cell over one second has been plotted. The cells show high load (Top), varying load (Middle), and low load (Bottom).

Source: Daniel Willkomm et al., “Primary User Behavior in Cellular Networks and Implications for Dynamic Spectrum Access”.
Representative Patterns of Traffic Load during 5 Days (Core Networks/Internet)

E-commerce website: 292 production web servers over 5 days. (Traffic varies by day/weekend, power doesn’t.)
Base Stations’ Traffic Loads Measurement Campaigns in Zhejiang (China)

- Traffic records from 9 MSCs and SGSNs with about 7000 BSs with coverage of 780 km²
- Both GSM and UMTS BSs traffic from January to December in 2012, serving about 3 million subscribers

Measured Traffic Loads Variation Patterns
(One Week)
Typical Examples of Measured Base Stations’ Traffic Loads in Zhejiang (China)

Sensing and Prediction of Cellular Networks’ Traffic Flows & Loads

\[ y_{1,t} = x_{2,t} + x_{3,t} \]

Interpolation: fill in the missing data from incomplete and/or indirect measurements of the Traffic Matrices
Sensing and Prediction of Cellular Networks’ Traffic Flows & Loads (2)

- Idea 1: Exploit low-rank nature of Traffic Matrices
  - Observation: Traffic Loads are low-rank in general

- Idea 2: Exploit spatio-temporal properties of the Traffic Matrices
  - Observation: Traffic Matrices’ rows or columns close to each other (in some sense) are often close in value (relevance)

\[
X = \begin{bmatrix}
\text{Missing} & x_{1,2} & x_{1,4} & x_{1,5} \\
& & & \\
& & & \\
& & & \\
\end{bmatrix}
\]

Note: In the context of matrices, low rank is analogous to sparsity, because the spectrum formed by the singular values of a low-rank matrix is sparse. It is now well known that the Traffic Matrices can be approximated by matrices of low rank.

Network Energy Saving through BS Switching on/off (Sleep Mode)
Block Diagram of Reinforcement Learning
- The learning system and the environment are both inside the feedback loop
Reinforcement Learning: Actor-Critic Approach

Observation ➔ Environment ➔ Reward ➔ Internal State

Policy ➔ Actor

Value Function ➔ Critic ➔ TD Error ➔ Cost ➔ Environment

state ➔ Environment ➔ Action ➔ Observation ➔ Reward ➔ Internal State
Stochastic BS Switching Operation with Actor-Critic Learning

Stochastic BS Switching Operation with Actor-Critic Learning (2)

Scenario

- A region $\mathcal{L} \in \mathbb{R}^2$ served by a set of BSs $\mathcal{B} = \{1, \ldots, N\}$;
- A BS switching operation controller to turn on/off some BSs in a centralized way;
- A traffic load density as
  \[ \gamma(x) = \frac{\lambda(x)}{\mu(x)} < \infty: \text{arrival rate per unit area} \lambda(x) \text{ and file size} \frac{1}{\mu(x)}; \]
Base Stations’ Traffic Load State Vector

- Traffic load within BS $i$'s coverage:
  $\Gamma_i = \int_{L} \gamma(x)I_i(x, B_{on}) \, dx$;
  - $I_i(x, B_{on}) = 1$ denotes location $x$ is served by BS $i \in B_{on}$

- Finite state Markov process (FSMC) to demonstrate the traffic load variation condition;

- Traffic load $\Gamma_i$ for BS $i$ is partitioned into two parts by a boundary point $\Gamma_b$.
Traffic Loads and BS Power Consumption Model

- **System load density** is defined as the fraction of time required to deliver traffic load $\gamma(x)$ from BS $i \in B_{on}$ to location $x$, namely $\rho_i(x) = \gamma(x)/c_i(x, B_{on})$.
- System load for BS $i \in B_{on}$: $\rho_i = \int_{L} \rho_i(x)I_i(x, B_{on})\,dx$.

**Power Consumption Model**

$$\psi(\rho, B_{on}) = \sum_{i \in B_{on}} \left[ (1 - q_i)\rho_i P_i + q_i P_i \right],$$

- $q_i \in [0, 1]$: the portion of constant power consumption for BS $i$;
- $P_i$: the maximum power consumption of BS $i$ when it is fully utilized.

$$\min_{B_{on}, \rho} \{ \psi(\rho, B_{on}) \},$$

s.t. $\rho_i \in [0, 1]$ $\forall i \in B$. 
Actor-Critic Learning: Markov Decision Process

An MDP $M = < S, A, p, C >$, 

- $S$: the state space;
- $A$: the action space;
- $p$: a state transition probability function;
- $C$: a cost function.
An MDP \( M = \langle \mathcal{S}, \mathcal{A}, p, C \rangle \),

- \( \mathcal{S} \): the state space;
- \( \mathcal{A} \): the action space;
- \( p \): a state transition probability function;
- \( C \): a cost function.
The goal is to find a strategy \( \pi \), which maps a state \( s \) to an action \( \pi(s) \), i.e., \( a^k \), to minimize the discounted accumulative cost starting from the state \( s \).

\[
V^\pi(s) = \sum_{k=0}^{\infty} \gamma^k C^k(s^k, \pi(s^k)|s^0 = s) \\
= C(s, \pi(s)) + \gamma \sum_{s' \in S} p(s'|s, \pi(s)) V^\pi(s'),
\]

where \( \gamma < 1 \) is the discount factor that maps the future cost to the current state.

The optimal strategy \( \pi^* \) satisfies the Bellman equation:

\[
V^*(s) = V^{\pi^*}(s) = \min_{x \in X} \left\{ C(s, \pi(s)) + \gamma \sum_{s' \in S} p(s'|s, \pi(s)) V^\pi(s') \right\}
\]
Actor-Critic Learning Scheme for BS Power Saving

Initialization:
for each \( s \in S \), each \( a \in A \) do
  Initialize state-value function \( V(s) \), policy function \( p(s, a) \)
end for

Repeat until convergent

1. Choose an action according to \( \pi^k(s^k, a^k) = \frac{\exp\{p(s^k, a^k)\}}{\sum_{a^k \in A} \exp\{p(s^k, a^k)\}} \);
2. Users connect some BSs by \( i^*(x) = \arg \max_{j \in B_{on}} \frac{c_j(x, B_{on})}{(1-q_j)P_j} \), \( \forall x \in L \) and then start data transmission;
3. Calculate the cost function \( C(s, a) \) by
   \( \psi(\rho, B_{on}) = \sum_{i \in B_{on}} [(1 - q_i)\rho_iP_i + q_iP_i] \);
4. Identify the traffic loads and accordingly update state \( s \to s^{k+1} \) and compute the TD error by \( \delta(s^k) = C^k(s, a) + \gamma \cdot V(s^{k+1}) - V(s^k) \);
5. Update the state-value function \( V(s) \) by \( V(s^k) \leftarrow V(s^k) + \alpha \cdot \delta(s^k) \);
6. Update the policy function \( p(s, a) \) by
   \( p(s^k, a^k) \leftarrow p(s^k, a^k) - \beta \cdot \delta(s^k) \).
## Numerical Analysis

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation area</td>
<td>1.5km * 1.5km</td>
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<tr>
<td>Maximum transmission power</td>
<td></td>
</tr>
<tr>
<td>- Macro BS</td>
<td>20W</td>
</tr>
<tr>
<td>- Micro BS</td>
<td>1W</td>
</tr>
<tr>
<td>Maximum operational power</td>
<td></td>
</tr>
<tr>
<td>- Macro BS</td>
<td>865W</td>
</tr>
<tr>
<td>- Micro BS</td>
<td>38W</td>
</tr>
<tr>
<td>Height</td>
<td></td>
</tr>
<tr>
<td>- Macro BS</td>
<td>32m</td>
</tr>
<tr>
<td>- Micro BS</td>
<td>12.5m</td>
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<tr>
<td>Intra-cell interference factor</td>
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<tr>
<td>Channel bandwidth</td>
<td>1.25MHz</td>
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<tr>
<td>File requests</td>
<td></td>
</tr>
<tr>
<td>- Arrival rate</td>
<td>$5 \times 10^{-6} \sim 10^{-4}$</td>
</tr>
<tr>
<td>- File size</td>
<td>100kbyte</td>
</tr>
<tr>
<td>Constant power percentage</td>
<td>0.1 $\sim$ 0.9</td>
</tr>
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</table>
Energy Saving by Actor-Critic Learning (BS Switching & Sleep Mode)

Performance comparison between Actor-Critic learning framework (LF) based energy saving scheme and the state-of-the-art (SOTA) scheme (JSAC, Sept. 2012) under various static/variant traffic arrival rates.

Basics and Advantages of Transfer Learning

Learning Process of Traditional Machine Learning

Different Tasks

Learning System
Learning System
Learning System

Learning Process of Transfer Learning

Different Tasks

Knowledge

Different Tasks

Learning System
Basics and Features of Transfer Reinforcement Learning

Source Task

Environment

Agent

Source Task Q-value Function Approximator

Action $a_{source}$

State $s_{source}$

Reward $r_{source}$

Target Task

Environment

Agent

Inter-Task Mapping

Source Task Q-value Function Approximator

Target Task Q-value Function Approximator

Action $a_{target}$

State $s_{target}$

Reward $r_{target}$

Action and State Variable Mappings
Features of Transfer Actor-Critic Learning
Algorithm 1 TACT: The Transfer Learning Framework for Energy Saving Scheme

Initialization:
for each $s \in S$, each $a \in A$ do
    Initialize state-value function $V(s)$, native policy function $p_n(s, a)$, and strategy function $\pi(s, a)$;
end for

Repeat until convergent

1) Choose an action $a^k$ in state $s^k$ according to $\pi(s^k, a^k)$;
2) Users at location $x$ connect one BS $i$ by $i^*(x) = \arg \max_{i \in \mathcal{B}_{on}} \frac{c_i(x, \mathcal{B}_{on})}{(1 - q_i)P_i}$, $\forall x \in \mathcal{L}$ and then start data transmission;
3) If $\rho_i \leq 1, \forall i \in \mathcal{L}$, the chosen action is feasible. The cost function $C(s^k, a^k)$ is calculated by $\sum_{i \in \mathcal{B}_{on}} [(1 - q_i)\rho_i P_i + q_i P_i]$; otherwise, an emergent response paradigm starts as the conventional scheme does.
4) Identify the traffic loads and accordingly update state $s^k \rightarrow s^{k+1}$ and compute the TD error by $\delta^k(s^k) = C^k(s^k, a^k) + \gamma \cdot V^k(s^{k+1}) - V^k(s^k)$;
5) Update the state-value function $V(s^k)$ by $V^{k+1}(s^k) = V^k(s^k) + \alpha(\nu_1(s^k, k)) \cdot \delta^k(s^k)$;
6) Update the native tendency function $p_n(s^k, a^k)$ by $p^{k+1}_n(s^k, a^k) = p^k_n(s^k, a^k) - \beta(\nu_2(s^k, a^k, k)) \cdot \delta^k(s^k, a^k)$, and update the function $p_o(s^k, a^k)$ by $p^{k+1}_o(s^k, a^k) = [(1 - \zeta(\nu_2(s^k, a^k, k)))p^{k+1}_n(s^k, a^k) + \zeta(\nu_2(s^k, a^k, k))p_c(s^k, a^k)]^{\nu_2(s^k, a^k, k)}$;
7) Update the strategy function $\pi^{k+1}(s^k, a) = \frac{\exp[p^{k+1}_o(s^k, a, k)/\tau]}{\sum_{a' \in A} \exp[p^{k+1}_o(s^k, a', k)/\tau]}$, for all $a \in A$. 
### Numerical Analysis

#### Used Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Value</th>
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<tbody>
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<td>Simulation area</td>
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<td>Constant power percentage</td>
<td>0.1 $\sim$ 0.9</td>
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</tbody>
</table>

*a For simplicity, we don’t consider fast fading effect and noise influence in our simulation.
Performance comparison among classical AC scheme, TACT scheme and SOTA scheme under various homogeneous traffic arrival rates when the transfer rate $\theta = 0.1$

Performance impact of the transfer rate factor $\theta$ to the TACT scheme when $\lambda = 5 \times 10^{-6}$

Summary & Conclusion

➢ **Environmental-friendly Green Communications:**
  – A paradigm change from traditional coverage- & capacity-driven to energy-efficiency driven communications and networks (Smart, sustainable, and self-harmonized greener ICT).

➢ **Cognitive Green Radio Communications:**
  – Besides spectrum and energy, intelligence is the **THIRD kind of resource**, but without limitation of scarcity.
  – Learning and decision making algorithms under green constraint can play a significant role in enabling energy- and spectral-efficient greener future communications.
  – Effective energy saving can be realized by using various learning approaches in mobile cellular networks.

**Cognitive Green Communications: From Concept to Reality!**
Thanks!

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