Extending the REpresentational State Transfer (REST) Architectural Style for Decentralized Systems

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Abstract

Because it takes time and trust to establish agreement, traditional consensus-based architectural styles cannot safely accommodate resources that change faster than it takes to transmit notification of that change, nor resources that must be shared across independent agencies.

The alternative is decentralization: *permitting independent agencies to make their own decisions. Our definition contrasts with that of* distribution*, in which several agents share control of a single decision. Ultimately, the physical limits of network latency and the social limits of independent agency call for solutions that can accommodate multiple values for the same variable.*

Our approach to this challenge is architectural: proposing constraints on the configuration of components and connectors to induce particular desired properties of the whole application. Specifically, we present, implement, and evaluate variations of the World Wide Web's REpresentational State Transfer (REST) architectural style that support distributed and decentralized systems.

1. Introduction

We are interested in designing decentralized software for a decentralized society — systems that will permit independent citizens, communities, and corporations to maintain their own models of the world. Portions of such applications must operate under the control of multiple, independent administrative authorities (agencies); and may be physically separated to the extent that communication latency between those parts becomes a significant factor in their design.

The state of the art in software engineering has long focused on designing solutions for *distributed* systems, where multiple agents share control of a single model. Unfortunately, this presumes it is always possible to establish consensus over the current value of a variable. Physics abandoned simultaneity with relativity in 1905; formal models of computing disproved consensus over faulty, asynchronous networks in 1985 [12]. Regardless of how dominant centralized client/server architectures may appear to be today, the physical limits of latency and the social limits of free agency will make decentralization inevitable for software as well.

Our approach to coping with uncertainty and disagreement is based on software architecture: constraints on configurations of components and connectors that induce desired properties of an overall system. This paper introduces several new architectural styles that are expressly designed to accommodate decentralization. First, we sketch a formal model of the problem that allows us to analyze the limitations of consensus-based architectural styles. Second, we address those limitations by identifying new architectural elements and constraints that could be added to an existing network-based architectural style to induce each of those properties. Third, we evaluated the feasibility of those newly derived styles by implementing infrastructure for, and applications of, each.

2. Problem Analysis

Like any other design discipline, software development is subject to the vagaries of fads and fashion. In recent years, there has been a surge in the popularity of the term 'decentralization': we hear of 'decentralized file-sharing,' 'decentralized supercomputers,' 'decentralized namespaces,' and a slew of 'peer-to-peer,' 'Internet-scale,' and 'service-oriented' architectures [8, 32, 33].

To date, the software engineering and software architecture literature has not embraced a formal definition of 'decentralization.' Indeed, in a full-text search of the ACM Digital Library, we found that it was often considered a synonym for 'distribution' until only recently. Even as of 1998, it only occurs once in the official ACM subject classification [1], and then only with respect to the organizational behavior of MIS departments [24].

Thus, our first goal is to provide precise, testable definitions. In this section, we will discuss the factors leading to decentralization (latency and agency); provide a formal definition of simultaneity in terms of the consensus problem; and use that to define the properties of centralized, distributed, estimated, and decentralized resources.

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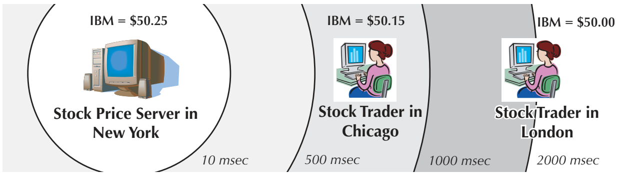

Figure 1: Latency induces uncertainty for traders "further" away from a centralized resource.

2.1 Latency

Latency makes simultaneous agreement impossible in many real-world situations. Consider how it affects a stock traded on the (distributed) NASDAQ market. A stockbroker in London interested in knowing the current price of the stock consults a server that broadcasts its current price. Realistically, Internet delays could range up to two seconds, or worse. If the actual price in New York were changing at up to 1 Hz, it would become impossible for the London stockbroker to know its *current* price.

The concentric circles in Figure 1 represent latencies (on a logarithmic scale). Their radii are correlated with distance, but more intriguingly, also determine the maximum update rate of an event source. We call this the 'now horizon', since it demarcates which components can reliably refer to the value of a variable 'right now.'

Latency is an absolute constraint for software architects because it takes time and energy to transmit information across a channel. It can be factored into three separate limits: propagation delay, bandwidth, and disconnection (longest tolerable interruption).

2.2 Agency

While latency is a physical limit, the concept of an agency is a socially constructed one. We are referring to the divergent interests of the organizations that ultimately own and operate the computers that software runs on [39].

An agency boundary denotes the set of components operating on behalf of a common (human) authority, with the power to establish agreement within that set and the right to disagree beyond it it.

Consider a database package. Run a 'local' copy for yourself, and then if you store `X=5`, then `5` is the one and only true value of `X`. Accessing the same application over a network, though, raises the possibility that the data may have been tampered with or biased. That is a profound difference between the output of the local database component ("*I* believe `X` *is* `5` now") and that of a remote database *service* ("Someone *else* claimed `X` *was* `5` then").

2.3 Simultaneous Agreement

> The impossibility of consensus is considered to be one of the most fundamental results of the theory of distributed computing [30].

In 1985, Fisher, Lynch, and Paterson proved that on a completely asynchronous network (one with maximum message latency $d=\infty$), if even one process can fail, then it is impossible for the remaining processes to come to agreement [12]. Lynch's textbook also includes a proof that even with a partially synchronous network (one with only a finite d), but with message loss or reordering, consensus still requires at least d seconds [30]. In general, tolerating f processes failing requires at least $(f + 1)$ additional rounds.

Even so, this model of consensus still does not ensure simultaneity. Some processes may decide sooner than others (e.g. because of varying network latency). Furthermore, if the shared value were modified, some processes may still be using the older value, even though others have moved on.

To formalize this condition, we borrowed the term "simultaneous agreement" from contract law. Stated as a condition on two separate variables, a leader and a follower, we define it as the interval satisfying this conjunction:

$$\exists\, t_0,\, t_i,\, t_j : (\, t_i \le t_j\,) \wedge (t_i \le t_0 + d) :$$
$$\forall\, v : t_i \le v \le t_j : \; P_{leader}(v) = P_{folbwer}(v)$$
$$\wedge\, \forall\, u : t_0 \le u \le t_j : \; P_{leader}(u) = P_{leader}(t_0)$$

That is, the follower's value must become equal to the leader's *before* it changes. In Figure 2, where world-lines are drawn vertically for the state of the leader and follower processes, this only holds in the shaded region.

Note that the second message's *lease* expires before it even arrives. In general, it is impossible to guarantee simultaneous agreement for any centralized resource that changes more frequently than $^1/_d$ times per second.

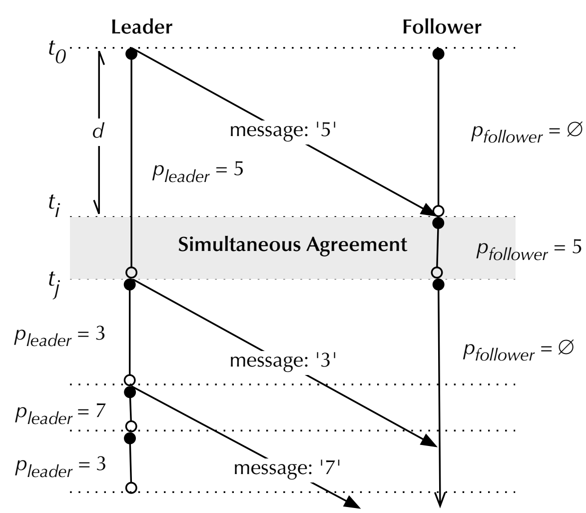

Figure 2: The shaded region illustrates an interval of simultaneous agreement.

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2.4 Definitions

Using our formal model of simultaneous agreement, we derived precise, declarative definitions of the properties of centralized, distributed, estimated, and decentralized variables in an expanded work [21]. For this paper, we opt for more concise, if less formal, definitions:

> A **centralized** variable requires simultaneous agreement between a leader and all of its followers.
>
> A **distributed** variable is determined by applying a shared decision function over all participants' inputs.
>
> An **estimated** variable is in simultaneous agreement only a fraction of the time.
>
> A **decentralized** variable is determined by applying a private assessment function over other trusted participants' variables (or estimates of those variables)

Another way of distinguishing these terms is by the degree of indirection required to implement each. The basic element of information storage is the *value*: centralization requires every agent to use the same value. This can be accomplished as simply as by connecting several devices to the same wire or other shared medium.[1]

The next level of indirection is a private namespace for storing values over time: the *variable*. In a distributed system, a closed group of agents uses a single logical name to refer to a shared variable — even though its actual value is not stored in one place, but rather in a set of 'shadow' variables held by each participant. Later, for an estimated system, there will still be one putative shared variable, but the local proxy may become less *precise*.

Decentralization depends on a third, additional distinction: a public namespace of *concepts* that may differ across agencies. An intuitive illustration is the difference between typing the address HTTP://WEATHER.ORG/LAX into a Web browser, and typing the concept "LA WEATHER REPORT" into a Web search engine's query box. The latter will return links to *many* different organizations' opinions of the weather in Los Angeles — but also to forecasts for Louisiana (which is also abbreviated LA).

3. New Consensus-Based Architectural Styles

Before we proceed to extend it, it behooves us to understand the properties that REST can induce on its own. We will then describe four different capabilities that can be added to REST: Asynchronous event notification; Routing messages through active proxies; Decision functions that select the current value of a shared resource; and Estimating current representations based upon past ones. Later, we will combine all of these basic facilities to derive a new style for decentralized systems.

[1] "A wire is just a renaming device for variables."
— Alain J. Martin, asynchronous VLSI designer [31]

3.1 Modern Web Architecture

There are many different network-based architectural styles, such as client-server and remote-data-access [9]. The style popularly known as "3-tier client/server" is a combination of both of those styles: presentation interface at a client, business logic on a server, and storage in a database. It was arguably the dominant style of application development until the mid-1990s, when it was eclipsed by architecture of the modern Web, as descibed by REpresentational State Transfer (REST, [11]).

In this style, software components are recast as network services. Clients request resources from servers (or proxy servers) using the resource's name and location, specified as a Uniform Resource Locator (URL, [3]). All interactions for obtaining a resource's representation are performed by synchronous request-response messages over an open, standard network protocol (HTTP/1.1, [10]). Requests can also be relayed via a series of proxies, filters, and caches, all without changing its semantics.

REST's essential distinction, though, is not found in such details. Rather, its layer of indirection[2] between abstract *resources* and concrete *representations* captured the Web's key insight for decentralizing hypertext — permitting *broken* links between independent sites [20].

Nevertheless, REST (and the Web, its archetypal application) still has significant limitations:

One-shot: Every request can only generate a single response; and if that response is an error message (or lost), there are no normative rules for proceeding.

One-to-one: Every request proceeds from one client to one server. Without a way to transfer information to a group of components, this leads to nested "proxy chains."

One-way: Every request must be initiated by a client, and every response must be generated immediately, precluding servers from sending asynchronous notifications. REST cannot model peer-to-peer relationships well.

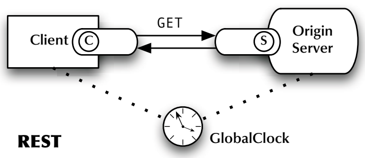
3.2 REST: REpresentational State Transfer

To ground our exploration of these new issues, we began by restating REST to verify that it could induce the property of consensus. Our more-rigorous correctness argument elucidated that REST depends on synchronized global clocks to ensure leases expire simultaneously.

Synchronization still presumes that every response message specifies its lease interval. Many real-world ORIGINSERVERs do not specify when the next permissible resource update is scheduled. The external environment could update resources at random (e.g. editing a file "by hand"). One solution is a *heartbeat:* defining a default lease duration and delaying updates until the next cycle.

[2] "Any problem in computer science can be solved by another level of indirection"— David Wheeler, chief prog., EDSAC [19]

Table 1: Summary of the REST architectural style.



Goal	Refer to a centralized resource.
New Elements	GLOBALCLOCK makes explicit how clients, servers, and caches are synchronized.
New Constraints	ORIGINSERVER must always specify a consistent expiry deadline if the resource is ever to be updated.
Induced Property	*Consensus:* Ensures that local resource proxies ***could*** agree with leader. [REST+Polling would guarantee it.]

As an aside, we have also developed a variation, REST with Polling (REST+P) that can induce a weak form of simultaneous agreement. With it, clients can follow leader values as long as the minimum lease interval is $3d$.

3.3 A+REST: Asynchronous REST

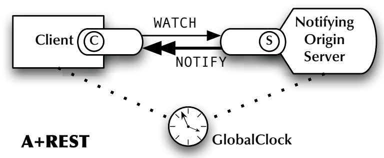
To achieve simultaneous agreement as quickly as theoretically possible (within d of any change), we propose an event-based approach that permits the central resource to *broadcast* notifications of its state changes. Our insight is to recast the concept of a resource in REST as an event source that emits event notifications corresponding to each change in its representation(s).

Rosenblum and Wolf [37] propose that "An *event* is the effect of the *termination* of an *invocation* of an *operation* on some *object of interest*…Events occur regardless of whether or not they're observed." Our stance is perhaps the opposite, insofar we consider that the very act of 'observation' to be what distinguishes events from messages. Specifically, our concern stems from the realization that 'on the wire,' there is little discernable difference between a messaging protocol and an event-notification protocol. However, there is a dramatic difference between the programming model for a batch message queue and an event handler. Thus, our view might be summarized as "*event notifications* are *messages* that cause *actions*."

In either case, though, there is a clear distinction between the *occurrence* of an abstract event and the concrete notification of an *observation* of one, as defined by the event lifecycle model of [36].

As illustrated in Table 2, a `NOTIFYINGORIGINSERVER` will transfer representations of *every* change to a resource as long as a client stays connected — a long-running `WATCH` request rather than a one-shot `GET`, with multiple `NOTIFY` replies. In practice, this is a significant implementation challenge across the public Internet [6].

Table 2: Summary of the A+REST architectural style.



Goal	Refer to a changing centralized resource.
New Elements	NOTIFYINGORIGINSERVER that can send multiple responses to a `WATCH` request.
New Constraints	Every resource update must lead to transmission of a new representation to all watchers.
Induced Property	*Simultaneous Agreement:* Ensures that local resource proxies ***will*** agree with leader's value, even if it is being updated at $1/d$ Hz.

3.4 R+REST: Routed REST

While A+REST tackled the essential challenge of latency, message routing will focus on improving REST's support for multiple agencies.

The specific property we intend to induce is *multilateral extensibility:* the ability to add functionality to an application using components owned by several different agencies. The complication is that new 3rd and 4th parties may be trusted by the original client or server, yet distrust each other.

The reason this becomes a problem for REST is that, while it offers exemplary support for "active proxies" to add functionality without modifying deployed applications, it can only arrange them in linear proxy chains [22]. This permits intermediaries to tamper with messages.

With redirection of replies depicted in Table 3, services can be composed while eliminating unjustified trust relationships — and minimizing total latency as well.

Composing multiple proxies, as in the simple chained evaluation of two functions owned by agencies *A* and *B* using data from a third, *C*. Figure 3 illustrates how the combination of Asynchrony and Routing leads to the highest performance: triangulation. It depicts five

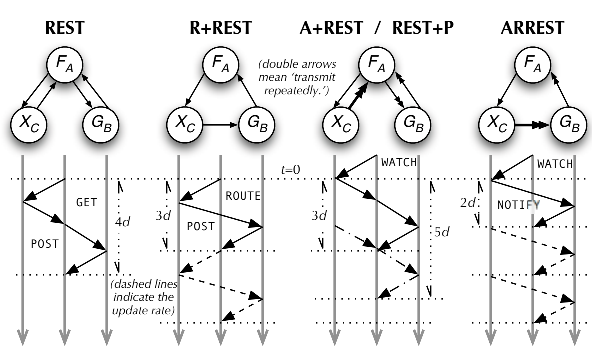


Figure 3: Latency of evaluating *F(G(X))* in several styles.

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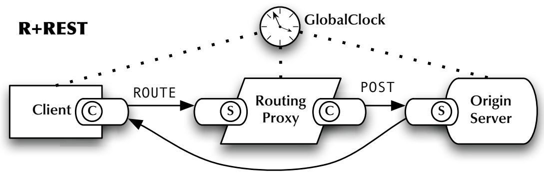
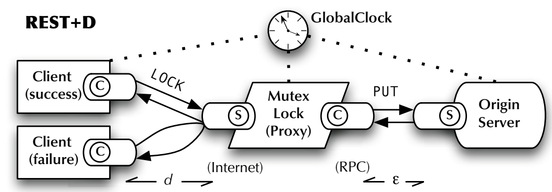
Table 3: Summary of the R+REST architectural style.



Goal	Compose services provided by multiple agencies.
New Elements	ROUTINGPROXY Component that permits clients to control relaying.
New Constraints	Every representation transfer must be justified by a corresponding edge in the web of trust.
Induced Property	*Multilateral Extensibility:* Can compose trusted invocations without requiring mutual trust.

Table 4: Summary of the REST+D architectural style.



Goal	Refer to a pairwise distributed read/write resource reliably.
New Elements	MUTEXLOCK Component ensures only one client at a time has write access to the origin server.
New Constraints	Lock must be acquired before attempting write. Current state of the resource must be read before attempting write.
Induced Property	*ACID (Pairwise) Simultaneous Agreement:* Clients can modify centralized resources within 3*d* — but only in the absence of contention.

approaches to the problem of computing $F_A(G_B(X_C))$: two using *read()*, which could fail; and three using some form of *subscribe()*. In the case of REST+P, the dash-dot line shows the worst case. In order to compare characteristic update frequencies, we did not count the initial *subscribe()* requests, by assuming they occurred beforehand.

3.5 REST+D: REST with Delegation

The earliest efforts to extend the Web to support authoring immediately ran afoul of the "lost update" problem. Two editors using local, cached copies could easily overwrite each other's work using a simple PUT. The typical criteria for judging a distributed database are the 'ACID properties,' standing for Atomicity, Consistency, Isolation, and Durability [16]. Most practical systems have to make tradeoffs in the degree of 'ACID-ity' to avoid tight coupling, though.

There is little an architectural style can do to enforce Durability (an implementation choice), or Consistency (an application-specific semantic). What REST+D *can* do is ensure total serialization of all updates to a resource.

The MUTEXLOCK Component is a proxy that wraps around an ORIGINSERVER to ensure mutually exclusive access. It contains an atomic test-and-set register identifying the only client whose request messages it will forward on to the ORIGINSERVER until instructed otherwise (or until the lock's lease expires). All other requests are simply discarded until the register is reset.

The general form of the styles we derived that share control of a resource among several peers is to add a Decision function. Delegation is one such, akin to transaction processing monitors that temporarily centralized control at one location for a commit protocol. ARREST+D, a more distributed solution, eliminates the need for a single event router by adding a Distributed lock protocol, such as Lamport's Bakery algorithm [28].

4. New Consensus-Free Architectural Styles

Beyond the 'now horizon' or beyond an 'agency boundary' there is uncertainty referring to any remote resource. Latency and agency induce different sorts of uncertainty, though: loss of precision vs. loss of accuracy.

Communication between components is subject to network loss, delay, and congestion, all three of which increase message latency. Depending on the degree of auto-correlation a resource exhibits, relying on older information can reduce the precision of local estimates.

Furthermore, once resources are decentralized into an ensemble of independently controlled, local resources, such estimates also become less accurate. That is because there is no single 'true' value any more, since *facts* will be replaced by a host of agency-specific *opinions*.

Our insight for managing the risk of computing without consensus is a counterpoint to the ACID properties for centralized and distributed systems. Our so-called 'BASE' properties require decentralized systems to rely solely on Best-effort network messaging; to Approximate the current value of remote resources; to be Self-centered in deciding whether to trust other agencies' opinions; and Efficient when using network bandwidth.

4.1 REST+E: REST with Estimates

Our first step is to improve the *precision*: minimizing the error between the current value of the local resource and the (single) remote resource it corresponds to. However, to better understand the role of estimation in everyday usage of the Web, we first specified REST+E, an elaboration of REST's default behavior once d=∞.

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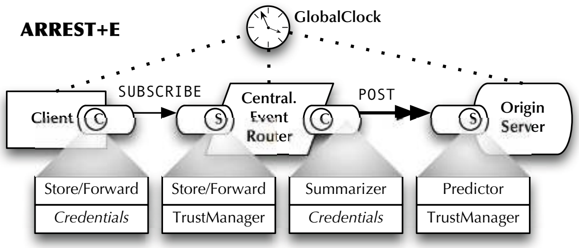
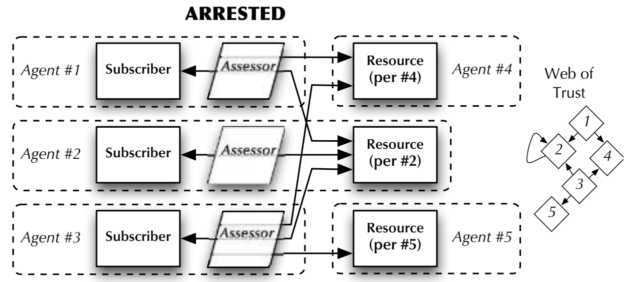
Table 6: Summary of the ARREST+E and ARRESTED architectural styles.





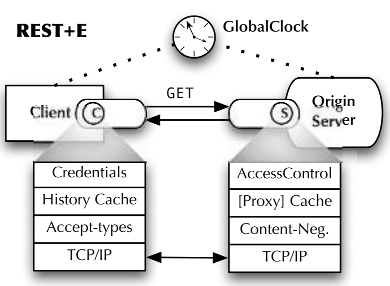
Goal	New Elements	New Constraints	Induced Property
Refer to a read/write resource connected by a faulty network beyond its now horizon.	StoreAndForward Connector that adds end-to-end retransmission & acknowledgement.	End-to-end retransmission of messages and acknowledgements.	*Best-Effort data transfer*: Cope with message loss.
	Predictor Connector for encapsulating Turing-complete prediction functions.	Predict probable current state from past data (where possible).	*Approximate estimates*: Cope with message delay.
	TrustManager Connector that drops notifications from untrusted sources.	Ensure that all reachable endpoints are also trusted.	*Self-Centered*: Cope with dynamic participation.
	Summarizer Connector to resample queued events at lower frequency, reduce size.	Prohibit transmission of already-expired data. Eliminate buffering.	*Efficient data transfer*: Cope with net congestion.
Decentralize control of a shared resource across disjoint 'now horizons'	Assessor Component that manages the risk of inter-agency disagreement over the 'true' value using a panel of opinions.	Eliminate reliable references to remote resources; only contingent assessments remain.	*Consensus-freedom:* avoid presuming feasibility of consensus.

Best-effort representation transfers are pushed down to the presentation layer of the network using TCP's sliding-window acknowledgement and retransmission protocols.

Approximate representations are returned by caches of several sorts: browser histories, caching proxies, and content distribution networks. Staleness is generally acceptable, even preferred in some cases.

Self-centered trust management is enforced by the use of server-based access controls, such as passwords.

Table 5: Summary of the REST+E architectural style



Goal	Refer to a read-only centralized resource beyond its now horizon
[Old] Elements	[TCP/IP], [Cache], [AccessControl], [ContentNegotiation]
New Constraints	Inertia assumes that the most recent representation is still valid, until cache revalidation fails.
Induced Property	*Approximate agreement:* The local proxy should be in simultaneous agreement *P%* of the time

Efficient representation formats are selected by client-driven content negotiation and compressed encodings.

4.2 ARRESTED: Putting it all together

We combined each these four basic capabilities to derive new styles from REST for centralized (ARREST), distributed (ARREST+D), estimated (ARREST+E), and decentralized resources (ARRESTED).

By combining asynchrony and routing, we created first-class subscriptions, which are the building block for familiar event notification services. Architects can specify simultaneous notification to a group of components using multiple, persistent subscriptions.

With an event-based style, it is easier to induce both ACID (ARREST+D) and BASE (ARREST+E) properties. In particular, End-to-end Estimator functions can manage private proxy resources that replace references to shared resources. The upper half of Table 6 describes components that can store-and-forward retransmissions of lost or delayed notifications, predict future values from past information already received, discard information from untrusted sources, and summarize past data so as to send only the latest information. Ultimately, summarizers could even take advantage of excess bandwidth to reduce latency further by speculating about *future* states as well [43]. All of these extensions to REST serve to increase *precision* of an estimate of a single remote resource (ARREST+E).

The ultimate challenge we must address, though, is aid architects in designing applications that accurately model even uncertain information in decentralized systems. Our proposal for increasing accuracy is to assess multiple, simultaneously valid opinions of the same concept from several agencies. If we presume the errors of measurement are independent — and we are speaking of decentralizing some concept that is at least conceivably centralizable (a price, rather than an arbitrary value) — then multiple observations can reduce total error.

Of course, such a Decentralized decision function may be as simple as taking the minimum, maximum, mean, median or mode; or as complicated as a Turing-complete simulation of an underlying physical process. Any of these, though, is preferable to blocking while waiting for a lock from a transaction manager.

5. Implementation Experience

Deriving new architectural styles and validating the properties they can induce by construction is only a conceptual exercise. It is at least as important to establish that all of these new components, connectors, and constraints are actually implementable; and that actual applications can be constructed in each of these styles.

5.1 Infrastructure

We have over five years of experience developing an experimental event-routing infrastructure along these lines. Eventually, that laid the foundation for the award-winning commercial edition sold by KnowNow, Inc [44].

The original prototype implementations were released separately as an open-source project in December 2002 called MOD_PUBSUB (by analogy to the Apache MOD_* naming convention for Web server extensions) [23]. As shown in Figure 4, it was developed in many languages.

Using MOD_PUBSUB with existing web tools and browsers, web pages can now respond to incoming events from the network — in real-time; in plain text, HTML, XML, and/or SOAP format; and without relying on Java or ActiveX in Mozilla, Netscape, *and* Microsoft browsers.

Both event notification services implement many of the component types introduced in §3 and §4, such as NOTIFYINGORIGINSERVER. Other elements are application-specific enough that they must be supplied by the architect, such as ESTIMATORs and ASSESSORs. Yet others appear as sample applications and reusable libraries, such as an implementation of STOREANDFORWARD called ZACK.

5.2 Methodology

Based on our experience writing decentralized applications, we can identify a few common issues that arose.

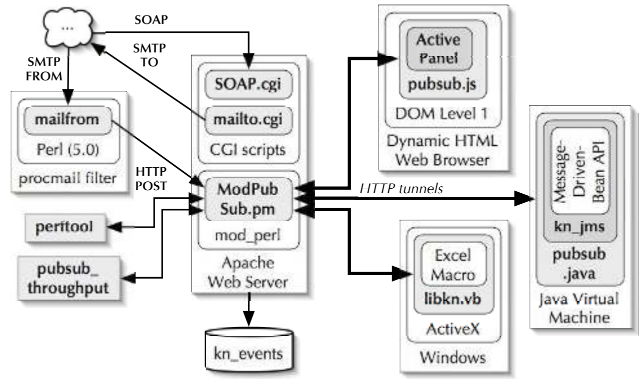


Figure 4: MOD_PUBSUB is an open-source ARREST toolkit.

Since ARRESTED is an event-based architectural style, the first phase of developing a decentralized application is still generic event-based analysis: identifying the components, event sources, subscription qualifiers, message formats, and the like. The second phase is a methodology specifically addressing unique concerns raised by decentralization. We propose five steps:

1. Identify the agencies. In any real marketplace, the interests of traders, brokers, and the exchange diverge significantly. Note that a single organization may develop the software used to enact all of these agencies' roles, but the design must remain robust in the face of independent implementations. Part of the challenge of developing architectural styles for decentralization is coming up with abstract models of software written by others.

2. Characterize the latencies. The next step is to characterize the latencies, both of the networks the application will run on top of, and of the real-world phenomena that it is attempting to represent. The latter may be more challenging: it may appear that the NYSE's ticker stops updating a stock's price on weekends, but the "after-hours" valuation may keep changing as news breaks.

3. Establish the web of trust. This requires more than merely authenticating credentials for each agency; it also determines which external resources ought to be considered "equivalent" to the same concept. This could range from lexical matching to 'Semantic Web' tags [2].

4. Eliminate remote references. This is the constraint unique to the ARRESTED architectural style: replacing all resources owned by external agencies with private assessments. Architects face tradeoffs between different prediction engines, compression engines, and other types of estimators; our style at least isolates such complexity.

5. Track the provenance of events. In an era of profligate computing resources, event notification is an appropriate use of surplus bandwidth, and audit trails are an appropriate use of surplus storage. Ideally, every datum displayed to a user interface ought to indicate its confidence interval. Furthermore, tracing ownership is essential for re-evaluating results after security breaches, cancellations, or anti-messages invalidate past data [18].

5.3 An Auto Auction Application

To experiment with our styles and methodology, we developed AUTOMARKET, a used-car auction marketplace.

Centralized. In the simplest mode, the owner of the central event router (web server) is the only agent that can set prices. We tested this by writing 'classified ad' events directly into files on the server's disk (no remote access).

Distributed. The next step is allowing multiple bidders to publish new bids to a shared topic. We tested this with both REST+D by relying on the central router to arbitrate the order bids arrived in and to guarantee delivery; and with ARREST+D by using our ZACK protocol to count acknowledgements from other traders.

Estimated. Since our example is not particularly high-frequency, the primary type of latency risk is disconnection rather than a few seconds' arbitrage. Per REST+E, AUTOMARKET defaults to a policy of inertia by displaying any recent bid within the last 24 hours. To experiment with ARREST+E, we connected the same feed to KnowNow's Excel spreadsheet adaptor and used its built-in time-series data to extrapolate current prices.

Decentralized. Finally, we adapted our user interface to work with generic concepts such as "truck prices." Rather than presenting price data for several different vehicles, we let users configure which types they considered to be "trucks" and calculated the average current price. Note that this did not rely upon bidders to classify what vehicles were trucks, nor upon "hidden hierarchy" in the router's topic names, but could be set individually by each trader.

Table 7: Experiments with AUTOMARKET in several styles.

	Claim	Experiment	Observation
ARREST	Simultaneous invocation of multiple services.	Operating the router like a 'classified ad' server by writing new BIDS directly to disk.	New information triggered updates on many users' displays; could invoke per-user active proxies like price and units conversion.
ARREST+D	Allow many clients to read *and* write to a shared ACID resource reliably.	Operating the router as a passive relay of BID events controlled directly by each user.	Event notification enabled users to update all copies of their BIDS in all other components as soon as possible.
ARREST+E	BASE allows disconnected users to predict current prices.	Connecting the prices to an Excel spreadsheet to plot trends; using constrained	Fitting a logarithmic curve allows SELLERS to model increasing-price auctions; buyers can place 'limit orders' in to cope with delays.
ARRESTED	Consensus-freedom permits assessment of concepts.	Deriving a private topic from the market according to a trader's rules.	Note how AUTOMARKET can provide synthetic estimates of the "truck" market, per each user's definition of a truck.

6. Related Work

While our definition of decentralization in terms of latency and agency, and our architectural approach towards addressing it may be novel, they are by no means the only models for managing the risk of disagreement.

6.1 Alternative Models of Decentralization

The literature of distributed computing includes many other formulations related to the consensus problem:

Byzantine Generals. In this problem, several parties must coordinate an attack simultaneously to win — but could also lie to each other [29]. The solution originally proposed is only robust against conspiracies of up to ⅓ of the generals. This can still suffice for read-only decentralized applications, such as file sharing [26].

Invariant Boundaries. First identified in [5] as the boundary between systems that agree on an invariant and those that cannot, it closely resembles our specific condition of simultaneous agreement. A more general condition applying to invariant boundaries was stated as the Consistency, Availability, Partitionability (CAP) theorem in [13] (later proven in [15]), which states:

> It is impossible to reliably provide atomic, consistent data when there are partitions in the network. It is feasible, however, to achieve any two of the three properties… most real-world systems today are forced to settle with returning "most of the data, most of the time."

Logical Clocks. Over the years, there have been many approaches that simulate the operation of a centralized, sequential processor atop a distributed processing network: logical clocks [27], virtual synchrony [4], and group communication [34].

Single-Assignment Variables. An architect could avoid disagreement entirely by restating the problem so as to eliminate mutable variables [42]. One example is the technique of single-assignment: rather than resetting the value of P_{leader} several times, a series of distinct variables could each be set just once: *First-*P_{leader}, *Second-*P_{leader}, and so on. Another approach is manipulating pointers to "future" values in parallel functional languages [17].

Peer-to-Peer Communication. [14] presents a formal model for peer-to-peer computing that uses variables to represent channels between peers. Casting communication channels as variables may make it clearer that the latency of network links also determines the maximum possible update frequency of any interaction across them.

6.2 Alternative Approaches to Decentralization

The challenge of decentralization recurs at many layers of abstraction in computing, from hardware to software:

Asynchronous VLSI. As semiconductor performance increases, it will become impossible to distribute a clock signal across a processor die, much less an entire system bus. This requires new kinds of 'self-timed' circuits [41].

Control theory. The study of feedback systems, also known as cybernetics, resulted in rules for assessing signals and estimating state with *observer variables* [40].

Internetworking. The breakthrough that permits interconnection of autonomous LANs is the *end-to-end hypothesis*: the notion that even an unreliable core can be used to synthesize reliable services, even without signaling.

Middleware. Application integration, even inside a single organization, faces barriers of interoperability and performance that led to a vast array of design patterns for message-oriented & event-based communication [38].

Mobile Systems. Caching and replication are optimistic strategies for managing inconsistency in disconnected operation, such as Bayou [7] or the Coda filesystem [25].

Software Architecture. Other researchers in the field has also described styles for managing latency, such as processing real-time news and data streams [35].

7. Conclusions

In this paper, we presented: a formal definition of decentralization; an analysis of the limitations of consensus-based software architectural styles; derivation of new architectural styles that can enforce the required properties; and implementations that demonstrate the feasibility of those styles and sample applications.

Figure 5 summarizes our findings. First, we identified two basic factors limiting the feasibility of consensus: latency and agency. These correspond to two boundaries, indicated by dashed lines: the 'now horizon' within which components can refer to the value of a variable 'right now'; and an agency boundary within which components can trust each other. Another way to describe them is that the now horizon separates consensus-based styles from consensus-free ones; and the agency boundary separates master/slave styles from peer-to-peer ones.

First, we identified four new capabilities that could be combined with REST individually to induce the properties we desired: events, routes, locks, and estimates. Then, we were able to combine these to derive four new styles optimized for each of the four types of resources.

For centralized resources, we enforce simultaneous agreement by extending REST into an event-based architectural style by adding Asynchronous event notification and Routing through active proxies (ARREST). For distributed control of shared resources, we enforce ACID transactions by further extending REST with end-to-end Decision functions that enable each component to serialize all updates (ARREST+D).

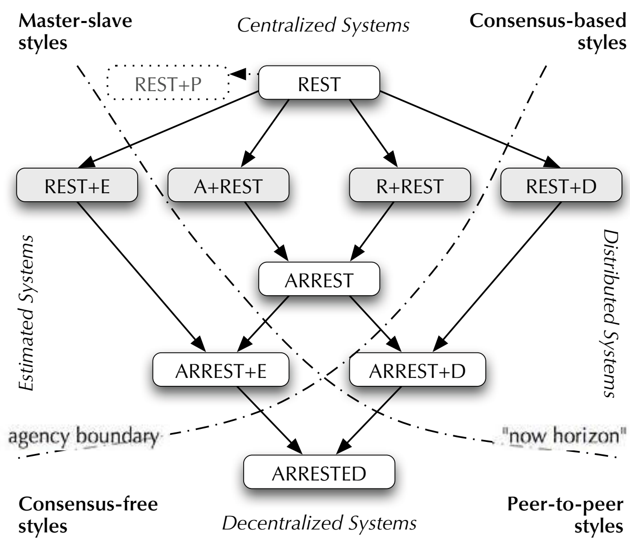


Figure 5: Diagram summarizing our four new architectural styles, derived from four capabilities added to REST.

The alternative to simultaneous agreement is *decentralization*: permitting independent agents to make their own decisions. This requires accommodating four intrinsic sources of uncertainty that arise when communicating with remote agencies: loss, congestion, delay, and disagreement. Their corresponding constraints are Best-effort data transfer, Efficient summarization of data to be sent, Approximate estimates of current values from data already received, and Self-centered trust management.

These so-called 'BASE' properties can be enforced by replacing references to shared resources with end-to-end Estimator functions. Such extensions to REST can increase *precision* of measurements of a single remote resource (ARREST+E); as well as increase *accuracy* by assessing the opinions of several different agencies (ARRESTED) to eliminate independent sources of error.

Furthermore, application of these styles to real-world problems has been shown to be both feasible and effective, using both open-source and commercial tools.

Acknowledgements

This work is based on the first author's doctoral dissertation, which also benefited from the support of Dr. André van der Hoek and Dr. Debra J. Richardson. The authors are also grateful for the assistance of Dr. Joseph Touch, Dr. E. James Whitehead, Dr. Roy T. Fielding, Eric M. Dashofy, Adam Rifkin, and our anonymous reviewers.

This material is based upon work supported by the National Science Foundation under Grant #0205724.

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