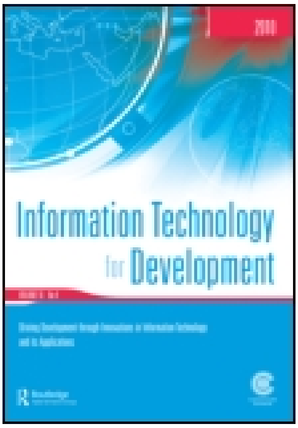

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Inferring patterns of internal migration from mobile phone call records: evidence from Rwanda

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Understanding the causes and effects of internal migration is critical to the effective design and implementation of policies that promote human development. However, a major impediment to deepening this understanding is the lack of reliable data on the movement of individuals within a country. Government censuses and household surveys, from which most migration statistics are derived, are difficult to coordinate and costly to implement, and typically do not capture the patterns of temporary and circular migration that are prevalent in developing economies. In this paper, we describe how new information and communications technologies (ICTs), and mobile phones in particular, can provide a new source of data on internal migration. As these technologies quickly proliferate throughout the developing world, billions of individuals are now carrying devices from which it is possible to reconstruct detailed trajectories through time and space. Using Rwanda as a case study, we demonstrate how such data can be used in practice. We develop and formalize the concept of *inferred mobility*, and compute this and other metrics on a large data set containing the phone records of 1.5 million Rwandans over four years. Our empirical results corroborate the findings of a recent government survey that notes relatively low levels of permanent migration in Rwanda. However, our analysis reveals more subtle patterns that were not detected in the government survey. Namely, we observe high levels of temporary and circular migration, and note significant heterogeneity in mobility within the Rwandan population. Our goals in this research are thus twofold. First, we intend to provide a new quantitative perspective on certain patterns of internal migration in Rwanda that are unobservable using standard survey techniques. Second, we seek to contribute to the broader literature by illustrating how new forms of ICT can be used to better understand the behavior of individuals in developing countries.

Keywords: ICTD; internal migration; migration; mobility; development

1. Introduction

A country's overall development trajectory is intimately connected to the way in which its inhabitants move about. Internal migration, defined as the temporary or permanent relocation of individuals within a country, can have a profound impact on regional labor markets (Borjas, 2006; Greenwood, 1985; M. Todaro, 1980),[1] affect levels of urban and rural inequality (Lucas, 1997), and provide vectors for disease transmission (Busenberg & Travis, 1983; Keeling et al., 2001), to name just a few examples. As a result, many governments in developing countries have gone to great lengths to regulate the movement of populations, instituting sometimes draconian, and often futile, policies to inhibit migration (Shrestha, 1987; Simmons, 1979).

As policy-makers and academics gain more insight into the consequences of migration, so too have researchers grappled with understanding the causes of migration (Borjas, 1999;

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Lucas, 1997). While the canonical model posits that individuals migrate primarily to earn higher wages (M.P. Todaro, 1969), more recent work has shown that the decision to migrate is far more complex. For instance, Munshi (2003) used longitudinal data from Mexico to show that the migrant's social network in the destination location had a large impact on his later success and subsequent migration decisions. Using cross-sectional data, a number of other studies have shown that migrants and non-migrants tend to come from different socioeconomic classes, different age groups, and different genders. More generally, it also appears that certain types of individuals are more likely to be more mobile on a daily basis, irrespective of more permanent migratory behavior (Frias-Martinez, Virseda, & Frias-Martinez, 2010; Maheswaran, Pearson, Jordan, & Black, 2006).

Despite the burgeoning literature on both the causes and effects of migration, the empirical methods used to measure and evaluate migration – and internal migration in particular – remain quite rudimentary. Over the past few decades, a number of prominent academics have pointed to the inadequacy of reliable data as a major constraint to research on migration (Banerjee & Duflo, 2007; Bilsborrow, 1997; Lucas, 1997; Massey, 1990; McKenzie & Sasin, 2007; Nelson, 1976). This constraint is exacerbated in developing countries, where limited infrastructure exists to coordinate migration-specific surveys.

In this paper, we discuss how new information and communication technologies (ICTs), and how mobile phones in particular, can provide researchers with new insight into patterns of migration and human mobility.[2] After discussing in greater depth the limitations of the current data (Section 2) and the advantages that ICT-generated data have over more traditional data (Section 3), we demonstrate the proposed empirical analysis using Rwanda as a case study (Section 4). We develop a new quantitative measure of *inferred mobility* that we use to compute rates of temporary and circular migration from call records that were obtained from the Rwandan telecommunications operator. Our results indicate that although rates of permanent internal migration are moderate, the rates of temporary and circular migration are much higher. We finish with a discussion of the implications of our findings to researchers interested in social development, and of the limitations of our methodology, with a particular focus on the ethical concerns arising in the use of ICTs to track movement (Section 5). Section 6 concludes.

2. The challenge of measuring internal migration in developing countries

Internal migration, both permanent and seasonal, is extremely common in most developing countries. For instance, Banerjee and Duflo (2007) note that 60% of the poorest households in Rajasthan, the largest state in India, report that someone from their family left the home for part of the year to obtain work. Aker, Clemens, and Ksoll (2011) observe that over 45% of households in Niger have at least one seasonal migrant, and Skeldon (1986) notes that roughly 30% of Indians reported permanently living in a place other than the place of survey enumeration. Though much of the policy debate surrounding migration has focused on urbanization and the permanent resettlement of citizens from rural areas to cities, empirical evidence suggests that rates of rural-to-rural migration may be much higher (Banerjee & Duflo, 2007; Cohen & Dupas, 2007).

Unfortunately, much of the empirical quantitative research has been hindered by a lack of reliable statistics on migration. Indeed, most developing country governments track only a handful of migration-related statistics (Lucas, 1997). Moreover, the statistics that do exist are potentially quite misleading. Part of the difficulty stems from the fact that migrants, by definition, leave one place and resettle in another, complicating the prospect of longitudinal interviews with migrants and adding bias to metrics that do not account for such movement. In discussing a long-term tracking study of migrants in Tanzania, Beegle, De Weerdt, and Dercon (2011) summarized the problem as follows:

> The costs and difficulties of resurveying means that attrition may be relatively high for [migrants] and may also result in the loss of some of the most relevant households for the study of this process . . . Had we not tracked and interviewed people who moved out of the community, a practice that is not carried out in many panel surveys, we would have seriously underestimated the extent to which poverty decreased . . . we would have reported poverty reduction at about half its true value. (p. 2)

In practice, migration-specific survey modules such as the one employed by Beegle et al. (2011) require considerable time and resources to deploy, and are prohibitively expensive for most researchers and government agencies. This is especially true in developing countries, which often lack the substantial administrative infrastructure required to develop an instrument, train enumerators, analyze the data, and otherwise coordinate (and fund) a large survey. Thus, the vast majority of research on migration relies at some level on aggregate population statistics such as censuses and population registers.

These aggregate statistics may be appropriate for certain lines of inquiry – for instance, they can describe rough patterns of international migration, and of net urban–rural migration, two phenomena that have been at the center of the policy debate on migration. However, the typical government census occurs only once every 10 years, and does not record fine-grained demographic shifts in the population. Censuses are also notoriously biased toward documented citizens, often failing to capture the extent and significance of undocumented or international migrants (Massey & Capoferro, 2004). More detailed surveys, when available, are often *ad hoc* and not standardized. For instance, a recent survey of worldwide statistics on internal migration found that of the 38 African countries studied, no more than 10 had a common definition of the requisite time interval required to qualify someone as a migrant (Bell & Muhidin, 2009). This inconsistency is not unique to Africa. Carletto and de Brauw (2007) note that only one country of the 89 they surveyed was compliant with the UN Recommendations on Statistics of International Migration. To give one final example, Lucas (1997), in his review of the migration literature, attempted to separate urban city growth into the components due to natural population growth and the component due to actual rural-to-urban migration. However, he found that only 29 countries worldwide had census data with sufficiently detailed questions to perform this decomposition.[3]

Of particular relevance to those interested in developing countries, standard censuses and population registers often fail to track patterns of temporary and seasonal migration. The difficulty arises because a seasonal migrant, who leaves his place of residence but returns every year, would not be noted in a standard survey or census, since the place of residence and of enumeration may not differ. Yet, these forms of migrations are extremely common in developing countries, and in Africa and Asia in particular (Nelson, 1976). Moreover, these distinctions are not without consequence. As Nelson (1976) observes, “people who regard themselves as sojourners in the city will seek different kinds of housing, demand fewer amenities and services, behave differently with respect to making friends and joining organizations, use accumulated savings for different purposes, and respond to different political issues and candidates than will people committed to the city as their permanent home.” (p. 721) We take these shortcomings of the migration data as motivation for the current research, which seeks to explore alternative mechanisms for gathering and analyzing data on internal migration.

3. How ICTs can provide better measures of migration and mobility

With the proliferation of mobile phones and other ICTs in developing countries, billions of individuals now carry devices that can record fine-grained information on the trajectories of those persons through time and space. The combined data from these individuals thus provides a rich source of information on patterns of migration and mobility. Moreover, many of these individuals are precisely those whom statistical agencies have found so difficult to survey, such as undocumented citizens and those living in extremely remote areas. There are, of course, significant privacy concerns that arise when any agency or organization keeps detailed records of individual's location. This is particularly true with data that are unobtrusively collected, and for which it is often impractical to obtain the informed consent of the subjects under study. Ethical concerns such as these are discussed in greater detail in Section 5.2.

In recent years, a small but vibrant literature has developed around the ways in which ICTs can be used to better understand patterns of human movement.[4] To date, such research generally employs two distinct sources of data. The first involves custom ICT-based deployments, where researchers give subjects devices or software that monitors movement and behavior. In an early example of such research, Eagle and Pentland (2006) gave 100 volunteer US students and faculty smart phones equipped with special software that continuously tracked the subjects' locations and phone-based interactions. They found that, given information about a subject's movements during the first half of a day, they could then predict the subject's whereabouts for the rest of the day with roughly 80% accuracy. Using a similar software given to 200 mobile phone users, Gonzalez, Hidalgo, and Barabási (2008) showed that despite the diversity of individual travel patterns, most humans follow simple and reproducible patterns.

The second approach to measuring mobility with ICTs, and the one which we utilize in the empirical analysis that follows, employs the data inadvertently generated in the everyday use of technology, and requires no special device or software to be given to the subject. For the study of populations in developing countries, the mobile phone is the obvious choice, with over five billion subscribers worldwide (77% of the world population) and roughly 68% penetration in the developing world.[5] More sophisticated Global Positioning System-enabled devices continuously record the exact geocoordinates of the subscriber, but even the most rudimentary mobile phone can be roughly located in space based on the cell towers which are used to route calls and data sent between the device and the network. Based on the sequence of towers which the individual uses, it is possible to later reconstruct the approximate path which that person traveled.

In urban areas, where towers are quite dense, the geographic precision of tower-based locational inference can be quite precise, though the resolution decreases in rural areas, where towers are sparser. To provide a more concrete example, Figure 1 depicts the approximate location of all mobile towers in Rwanda circa 2008. Each dot represents a single tower and the straight lines demarcate the Dirichlet cells corresponding to the approximate coverage region of each tower. The urban capital of Kigali is evident in the dense cluster of cells in the center of the figure. In Figure 2, we superimpose on the Voronoi diagram the trajectory of two mobile subscribers over a 4-year period from early 2005 through late 2009. For each month in that period, we extrapolate the approximate location of the individual (based on the individual's center of gravity, a concept that is defined formally in the following section), and plot that point on the Rwandan map. Early locations are colored dark red, while later locations are yellow; subsequent month locations are connected with a solid line. The first figure depicts a typical individual living in the urban capital, who remains in roughly the same location over the 4-year period. The second figure shows an individual who is seen to migrate twice, once in mid-2006 and again in early 2008.

Using data of this nature, it is possible to measure the patterns of mobility and migration at a level of precision and temporal resolution that would be impossible using standard survey methodologies. To date, however, we are aware of only two studies have utilized individual movement logs to analyze patterns of mobility. In the first, Eagle, Montjoye, and Bettencourt (2009) compared usage trends between urban and rural citizens of a small developing country, and showed that individuals in rural areas travel significantly more per month than individuals in the cities, noting this "could be due to the small potential distances that can be traveled within the capital and the much larger distances within rural areas" (p. 146). Using similar data

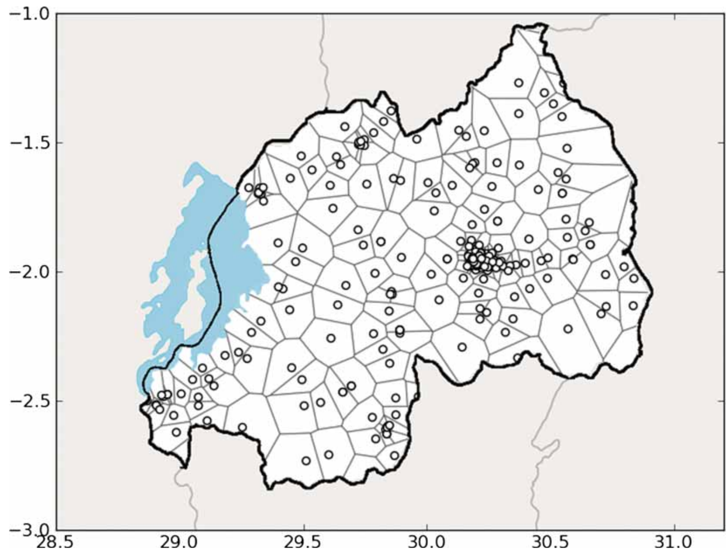

Figure 1. Map of Rwandan cell phone towers, January 2008. The median area covered by each tower is roughly 70 km^2.

from the "main city of a Latin-American country," Frias-Martinez et al. (2010) showed that people from areas of higher socio-economic status tend to be more physically mobile than people from poorer parts of the same city. Though both of these studies are evocative examples of the richness of the data, neither focuses on the phenomenon of internal migration, and both stop short of providing links to the broader development discourse. In the next section, we expand upon the work of these researchers, using similar data from Rwanda to very precisely quantify different aspects of internal migration in the country. When possible, we compare our results to official statistics from population censuses and household surveys.

4. Case study: measuring internal migration and mobility in Rwanda

In Rwanda, as in much of sub-Saharan Africa, rates of both internal and international migration are quite high. The upheaval surrounding the 1994 genocide created a massive refugee crisis that left almost 100,000 children orphaned, and dramatically altered the demographic composition of the population. However, the country has been relatively stable for the last decade, and during the period of time upon which we focus (2005–2009), anecdotal evidence suggests that patterns of migration appear to be comparable to those of neighboring countries (Nkamleu & Fox, 2006). Such broad generalizations notwithstanding, the actual quantitative evidence on migration in Rwanda, and in particular of the internal migration of Rwandans, is extraordinarily limited. In fact, the only relevant data we are aware of come from a pair of surveys conducted by the Rwandan government in 2006 and 2009. The Comprehensive Food Security and Vulnerability Assessment & Nutrition Survey (CFSVANS), which was conducted on a sample of 5400 households, asked a small number of questions about temporary and seasonal migration (National Institute of Statistics of Rwanda, 2009). Based on these data, the statistical agency reports that 12% of the households had at least one member who moved or migrated during the 3-month period prior to the survey, with 11% migrating within Rwanda. Numbers are similar in nearby Kenya, with Owen, Brey, and Oucho (2008) reporting that 8% of individuals aged 15 and older had moved to a new district in the year before the census. In neighboring Uganda,

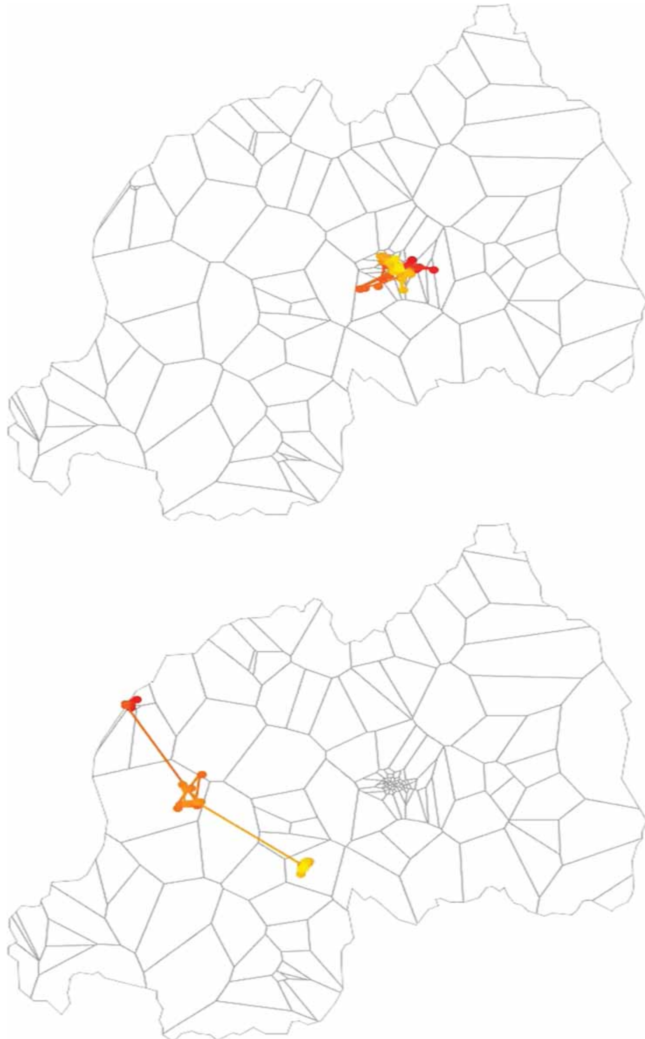

Figure 2. Movement of two different individuals in Rwanda over four years. Each vertex represents that individual's centre of gravity for a single month, with subsequent months connected by edges. Early months are colored dark red, with later months appearing orange/yellow. Approximate monthly locations are inferred from the individuals' history of phone calls using a procedure described in Section 4.

data from the 2002 census suggest that 12.8% of Ugandans live in a region other than the one in which they were born, with 5.5% having migrated in the five years prior to the survey (Ugandan Bureau of Statistics, 2002).

While these numbers provide a useful baseline for understanding internal migration in Rwanda, there are many fundamental questions that remain unanswered. For instance, what would the migration rate be if it were measured at a different time of year? How long do individuals stay in the destination location, and what percent of migrants eventually return to the place of origin? How do these numbers compare with more sophisticated mobility-related metrics such as migration intensity, the radius of gyration (ROG), and the index of net velocity? In the following sections, we demonstrate how mobile phone records collected by telecommunications operators can be used to answer questions such as these.

4.1 *Data*

The data we employ in the empirical analysis come from two distinct sources. First, we obtained from Rwanda's primary telecommunications operator an exhaustive log of all phone-based activity that occurred from the beginning of 2005 through the end of 2008. For each mobile phone user that was active during that period, we have a time-stamped record of every call that the individual made or received. Further, for each phone-based transaction that was routed through a cell phone tower (such as a phone call or text-message), we know the closest tower to the subscriber at the time of the transaction. This allows us to approximately infer the location and trajectory of roughly 1.5 million mobile subscribers over time and space, in a manner depicted in Figure 2.[6] However, it is important to note that we only have an intermittent signal of the individual's location. When the person goes for long periods of time without using his phone, he is effectively "off the radar" and his location is unknown. We will deal with the empirical and analytical implications of this intermittency in later discussions.

For the purposes of our empirical analysis, a limitation of the data we employ is that all of the records are entirely anonymous and contain no identifying or demographic information on any of the subscribers. Since we are interested in disaggregating patterns of mobility by demographic type, we have supplemented the anonymous data set with data gathered during a large-scale phone survey that we conducted in Rwanda in 2009 and 2010. For this survey, we obtained the mobile phone numbers of a small random sample of mobile subscribers and called these individuals to request a short, structured interview. To help preserve the confidentiality of the respondent, we did not collect identifying information such as the subscriber's name or address. In total, and with the help of an excellent group of enumerators from the Kigali Institute of Science and Technology, we completed 901 interviews on a geographically stratified sample of the population of mobile phone users.

Thus, for the 901 individuals surveyed we know his or her basic demographic information, as well as the rough pattern of movement over a 4-year period. For the remaining 1.5 million individuals who were not contacted in the phone survey, we have the movement histories but no associated demographic information. In interpreting the empirical analysis that follows, it is important to note that, as shown by Blumenstock and Eagle (2010), mobile phone subscribers in this region are different from non-subscribers – namely, they tend to be wealthier, older, better (formally) educated, and are more likely to be male. As mobile phone penetration approaches 100%, this distinction will gradually disappear. However, given the nature of our sample, the external validity of our results applies to mobile phone users in Rwanda, which during the period of time under analysis represented between 3% (in 2005) and 24% (in 2009) of the population. Since mobility is generally positively correlated with socioeconomic status (Frias-Martinez et al., 2010), we would expect the mobility of the at-large population to be lower.

4.2 *Methods*

Using the data described above, we compute and analyze a number of different metrics related to the migration and mobility patterns of phone owners in Rwanda. Since our data come from a single country, we focus on internal migration, and the pattern of movement within the country. We compute the following statistics based on the mobile phone transaction history:

Number of cell towers used: As a very crude proxy for the movement of the individual, we simply count the number of unique towers used by the individual during the specified interval of time.

Maximum distance traveled: This is the maximum distance between the set of towers used by the individual over the interval under study.

Radius of Gyration (ROG): While the preceding measures are quite simple, both have severe limitations, for instance that the number of towers used will be much higher for an individual living in an area with many towers, and the maximum distance traveled will be higher for an individual who uses his phone more often. Thus, we additionally compute a third metric that is more robust to intermittency and which accounts for the distance between towers. As discussed in greater depth by Gonzalez et al. (2008) and Song, Qu, Blumm, and Barabási (2010), the ROG is a concept borrowed from Physics which measures how far an object travels from its center of gravity. In the case of humans, the ROG roughly measures the typical range of a user in space. A person's center of gravity is the weighted average of all of the points from which the individual makes or receives a call, where the weight is determined by the number of times the individual calls from each location. Formally, we denote an arbitrary point in space (within Rwanda) by the vector r. Then, if an individual i makes N_i calls from locations $(r_{i1}, \ldots, r_{iN_i})$, that individual's center of gravity is the vector $\mathrm{COG}_i = (1/N_i)\sum_{t=1}^{N_i} r_{it}$. The ROG is then the root mean square distance of all of the other locations the individual visits from his center of gravity:

$$\mathrm{ROG}_i = \sqrt{\frac{1}{N_i}\sum_{t=1}^{N_i} (r_{it} - \mathrm{COG}_i)^2}. \tag{1}$$

While other measures of mobility exist, we selected these three because they are relatively simple and are among the most commonly employed in the literature. Moreover, many of the different mobility metrics are highly correlated, and we expect most findings to be robust to other definitions of mobility.

Inferred migration: While the mobility metrics are relatively objective to compute, the measurement of migration is less clear cut. As noted earlier, many countries use varying definitions of a "migrant" in reporting aggregate levels of migration. We define a new measure of *inferred migration* which we use to infer from an individual's call records whether or not he or she migrated in a given month. We employ a fairly flexible formulation which defines a migration as occurring at month m if the individual remained in one location for a fixed number of β months prior to m, and was also stationary for β months after and including m, but that the locations pre- and post-m were different. We call two locations r_1 and r_2 the same if the distance between them is less than the individual's ROG times a constant δ. Formally, we denote i's center of gravity in month t by COG_{it}; an inferred migration M_{im} occurs in month m if the following three inequalities hold:[7]

$$|COG_{im} - COG_{i(m-1)}| > \delta * ROG_i \tag{2a}$$

$$|COG_{i(m-s)} - COG_{i(m-s-1)}| < \frac{\delta}{\beta}\sum_{t=1}^{\beta} ROG_{i(m-t)}\,\forall\, s \in [1, \ldots, \beta] \tag{2b}$$

$$|COG_{i(m+s)} - COG_{i(m+s-1)}| < \frac{\delta}{\beta}\sum_{t=0}^{\beta-1} ROG_{i(m+t)}\,\forall\, s \in [1, \ldots, \beta] \tag{2b}$$

The intuition behind this definition of migration is that it accounts for the fact that, in the course of everyday events, different individuals travel different distances (their radii of gyration). The parameters β and δ allow for a flexible definition of migrant, for instance to account for the difference between a short-term and long-term migrant, and will be discussed in greater detail below. Finally, since we are interested in identifying changes in the individual's place of residence, rather than where they spend their work-days, we restrict our analysis to those phone-based transactions that occur between 7 pm and 7 am. However, this last restriction proves to be immaterial, and our quantitative results change very little if we include transactions occurring between 7 am and 7 pm.

4.3 *Empirical results*

4.3.1 *Population aggregates*

We begin by computing base rates of internal migration from the mobile phone data for the representative sample of 901 mobile phone users. Unless noted otherwise, we denote by $\bar{X}$ the population average of X across all n individuals sampled, in other words $\bar{X} = (1/n) \sum_{j=0}^{n} X_j$. Superficially, since we are producing population aggregates, it is possible to compare the statistics we compute with those measured by the Rwandan government using household survey data. However, it is critical to keep in mind that we do not expect the actual numbers to match, since our sample is from the population of mobile phone users in Rwanda, whereas the CFSVANS data were drawn from a representative sample of all Rwandans. This caveat in mind, the basic migration metrics are provided in Table 1. In Panel A, we reproduce the government estimates from the 2006 and 2009 waves of the CFSVANS. In Panel B, we compute the base migration rate $\overline{M_T}$ for short-term ($\beta = 2$ and $\beta = 3$) and long-term ($\beta = 12$) migrations.[8] Comparing between Panel A and Panel B, our estimate of a 6.17% migration rate in the three months prior to March is considerably lower than the 11.16% rate reported by the government survey. However, a closer analysis of Panel B reveals just how arbitrary the definition of migration can be. When a migration is defined as a minimum stay of 2 months, the migration rate is much higher at 12.21%; when a migration is defined as a minimum stay of 12 months, the migration rate drops to only 1.67%.

The inflexibility of the aggregate migration rate reported by the Rwandan government is further evident when we analyze temporal and seasonal changes in migration rates. For this exercise, we draw a random sample of 10,000 mobile phone users who are known to be active during the entire period from mid-2005 through late-2008.[9] In Figure 3, we re-compute the short-term migration rates (2 month and 3 month) for every month in the interval. It is evident that the internal migration rate varies considerably over time, with the 2-month rate ranging from a high of 13.09% in November 2005 to a low of 8.72% in August 2008.[10]

4.3.2 *Temporary and circular migration*

As empirically demonstrated above, and as discussed extensively in prior sections, the "standard" aggregate migration statistics provided in a typical census or survey are quite blunt

Table 1. Official and inferred migration rates in Rwanda.

	Panel A: Official migration rates from the Rwandan government		
Data Source	CFSVANS 2009	CFSVANS 2009	CFSVANS 2006
Statistic	Household member migrated internally from 12/08 – 2/09	Household member works away from homestead (ever)	Household member migrated internally from 1/06-3/06
Percentage	**11.16%**	**7.0%**	**10.23%**
	Panel B: Inferred migration rates computed from call records		
Data Source	Call Records	Call Records	Call Records
Statistic	Inferred migration $\overline{M_T} T = [12/07 - 2/08]$ $\beta = 2, \delta = 1$	Inferred migration $\overline{M_T}\ T = [12/07 - 2/08]$ $\beta = 3, \delta = 1$	Inferred migration $\overline{M_T}\ T = 1/05 - 12/08$ $\beta = 12, \delta = 1$
Percentage	**12.21%**	**6.17%**	**1.67%**

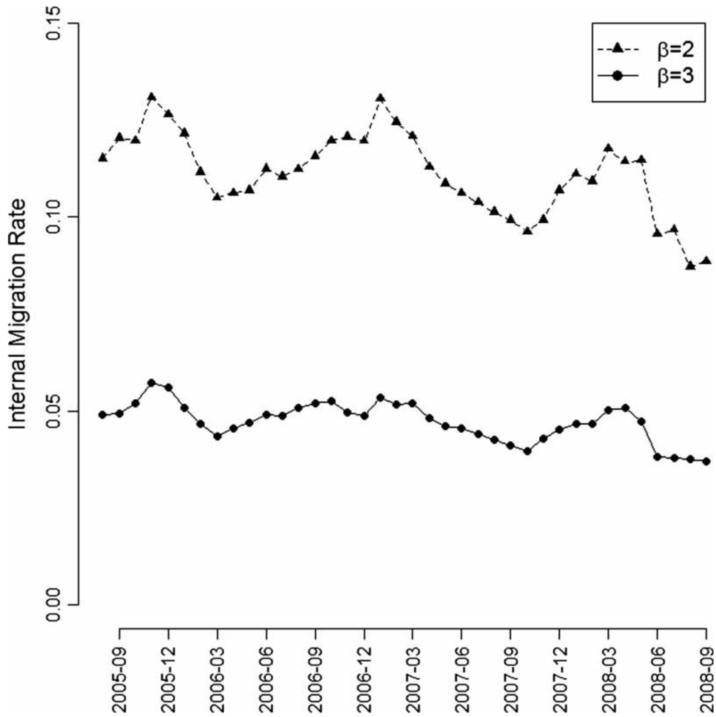

Figure 3. Internal migration rate in Rwanda over four years, as computed from call data.

instruments that are highly sensitive to the way the statistic is defined, and which overlook many of the important nuances of human mobility and migration. One particularly neglected aspect of migration emphasized in the literature is the temporary and circular migration that is quite common in many African nations (Baker & Aina, 1995; Nelson, 1976). Summarizing this deficiency, Lucas (1997) observes, "Circular migration – returning to an initial residence – can normally only be detected in specialized surveys, since initial residence and place of enumeration do not differ. In consequence, the extent of circular migration, in the developing world or elsewhere, is not always appreciated." (p. 729)

Using the call record data, however, it is possible to very accurately observe not only when an individual migrates, but also where the person goes, and whether the person returns to the place of origin or destination multiple times. Using a slight variation of equations (2a)–(2c), we separately quantify levels of temporary and cyclical migration. Namely, given that conditions (2a)–(2c) are met and $M_{im} = 1$, i.e. that i changed locations at month m and that i remained for at least β months in both locations, we consider M_{im} to be a *temporary* migration if i stays at the new location for no more than γ months, where γ typically is between 3 and 12 months, to be in accord with the UN Recommendations on Statistics of International Migration (United Nations, 1998). Furthermore, we consider M_{im} to be a circular migration if i has previously visited the new location, i.e. the new COG_{im} is within ROG_i km of COG_{it} for any t prior to m.

Table 2 summarizes patterns of temporary and circular migration in Rwanda for the random sample of 10,000 mobile subscribers who were active over the entire 4-year window.[11] Although only a very small percentage of these individuals permanently migrated a distance beyond their normal travel radius, nearly one-third of these individuals migrate temporarily at least once

Table 2. Permanent, temporary, and return migration rates for 10,000 random users.

	Percent of individuals with one or more (%)	Avg. # of migrations per migrant	Standard deviation
Permanent (12+ month) migration	**1.74**	1.02	0.13
Temporary (3–12 month) migration	**31.98**	1.47	0.76
Multiple (3+ month) migrations	**11.44**	2.37	0.65
Circular (return) migration	**6.45**	1.49	1.04

during the 4-year window, and roughly 11% migrate more than once during the same window. These numbers are considerably higher than one might be led to believe based on the aggregate statistics captured in the CFSVANS survey. Also striking is the pattern of circular migration evident in Table 2. Though the unqualified rate of circular migration that we estimate is only 6.45%, it must be kept in mind that we observe only a 4-year window of time, and at least two distinct migrations must be observed in that short interval for a person to potentially be a return-migrant. Thus, an alternative interpretation for these statistics is to note that over half (roughly 56%) of those individuals who migrate more than once will return to the place from which they left, all within a 4-year period. Taken together, this evidence suggests that even though the aggregate rates of migration reported by the government may be modest, there is quite a bit of action that is simply unobserved, particularly in the form of temporary and return migration.

4.3.3 *Disaggregating aggregate levels of migration and mobility*

One of the most robust findings in the migration literature is that all types of individuals are not equally likely to migrate. In most contexts, men are found to be more likely to migrate than women (Baker & Aina, 1995; Pedraza, 1991), and (with exceptions) most of the empirical evidence suggests that better educated people are also more likely to migrate (Lucas, 1997, pp. 73–74). In Rwanda, the CFSVANS final report notes that there is also significant heterogeneity by age. Specifically, "the 15–19 year olds were rarely identified as a main migrant group (6% of the communities). But migration was most frequent amongst the 25–29 age group (33%) followed by the 20–24 age group (30%)." (p. 44) Before concluding, we briefly test these hypotheses using the Rwandan call records.

In Table 3, we present the full set of migration and mobility metrics for the population of 901 respondents, and disaggregate the measures by the demographic groups described above. Surprisingly, we note that there only very modest differences exist between men and women in levels of migration and mobility, and that none of the differences are statistically significant.[12] Breaking the population down by education and by wealth, we observe that there are large and significant differences between the educated and uneducated, and between the wealthy and the poor. Specifically, it appears that the wealthy and the better educated are more likely to migrate for short periods of time. The better educated are also marginally more likely to migrate permanently (for periods exceeding 12 months), but the same cannot be said of the rich in comparison to the poor. Furthermore, based on the ROG evidence, we note that although individuals who complete secondary school are more than twice as mobile, on an everyday basis, as people who did not finish primary school, the rich and poor are statistically indistinguishable in terms of everyday mobility. Finally, Figure 4 provides a visual corroboration of the claim made in the CFSVANS report. While most individuals aged 20–50 are similarly mobile, the demographic groups at the upper and lower end of the age distribution have considerably smaller radii of gyration.

Table 3. Average mobility and migration metrics by demographic type.

	All	Gender		Education		Wealth	
		Men	Women	Did not finish primary school	Finished secondary school	Top 10%	Bottom 10%
ROG (km)	15.32	15.7	14.5	11.1***	20.4***	17.7	14.8
# towers	14.02	14.1	13.7	9.01***	23.7***	24.6+++	14+++
Max distance (km)	71.62	72.4	69.7	51.6***	96.3***	83+	70.9+
3-month migration	0.23	0.22	0.25	0.12***	0.48***	0.38+++	0.19+++
12-month migration	0.016	0.016	0.016	0*	0.032*	0.044	0.022
N	901	645	256	139	95	90	90

Notes: *,**,*** indicate means of male and female respondents different with $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively. +,++,+++ indicate means of top 10% and bottom 10% of the wealth distribution are different with corresponding levels of confidence. 3- and 12-month migrations correspond to $\bar{M}$ with $\beta = 3$ and $\beta = 12$, respectively.

One possible explanation for the differences evident in Table 3 and Figure 5 is that an omitted variable is driving much of the population heterogeneity. The most obvious such omitted variable would be the individual's occupation, with certain types of professions (such as truckers and taxi drivers) more likely to be mobile, and other professions (such as farmers) more likely to be stationary. Thus, in Table 4, we disaggregate the mobility and inferred migration statistics by occupation, for five of the most common occupations in Rwanda. Though for many professions the differences are minor, a few patterns emerge. First, farmers are much less mobile than the general population of phone users, and they are significantly less likely to temporarily migrate. This latter result is probably due to the fact that much of the Rwandan economy is based on subsistence farming, and the progressive land titling policies

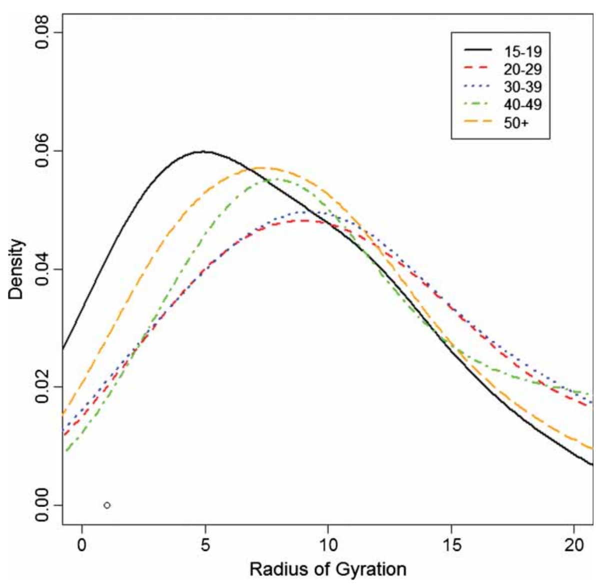

Figure 4. Distribution of ROG for different age groups.

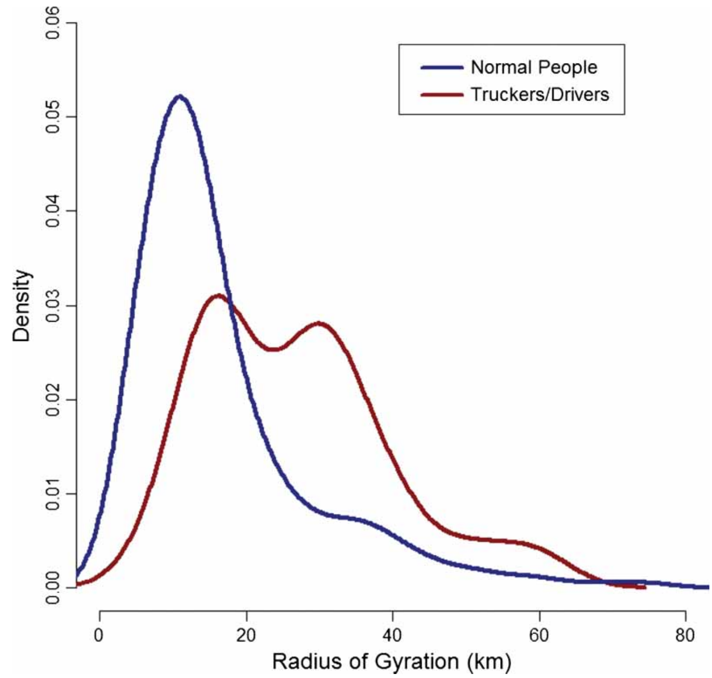

Figure 5. Distribution of ROG for individuals of different occupations.

Table 4. Average mobility and migration metrics by occupation.

	All	Farmer	Teacher	Student	Unemployed	Transport
ROG (km)	15.32	13.57*	15.81	18.94*	17.15	26.01**
# towers	14.02	8.99***	11.39**	15.97	15.06	40.04***
Max distance (km)	71.62	60.79***	77.03	74.76	76.69	111.84***
3-month migration	0.23	0.14***	0.28	0.22	0.28	0.39
12-month migration	0.016	0.01	0.01	0.00***	0.02	0.09
N	901	269	109	77	47	23

*Indicates mean of occupation is different from mean of group with $p < 0.05$.
**Indicates mean of occupation is different from mean of group $p < 0.01$.
***Indicates mean of occupation is different from mean of group $p < 0.001$.

have resulted in a large proportion of farmers owning land. Though migrant farmers do exist, they are perhaps less likely to own mobile phones and therefore less likely to be represented in our sample. On the other end of the spectrum, truckers and others in the transport industry are, as can be expected, significantly more mobile than normal citizens, by all three metrics of mobility (see also Figure 5). However, they do not migrate significantly more than people in other professions.[13]

5. Discussion

The preceding section illustrates how the rich data generated in the everyday use of mobile phones can provide a new perspective on patterns of migration and mobility in developing countries. Though the methods and metrics presented can certainly be further refined, the analysis highlights a number of aspects of internal migration –particularly with respect to temporary and circular migration, and to the heterogeneity of migrants – that are quite difficult to investigate using the data typically collected in government censuses and household surveys.

5.1 *Implications for social and human development*

A common critique of the development discourse is that it focuses too heavily on readily available metrics, placing an overemphasis on factors such as income and growth (cf. Sen, 1999). As Qureshi (2009) recently summarized, "some authors suggest that governments make policy based on discourse that has recourse to neat, easily available and powerfully constructed sets of institutional, legislative, and financial resources." (p. 1) As is evident in the recent emphasis on the Millennium Development Goals, policy-makers are actively interested in expanding the array of quantitative metrics, to better address the social and human aspects of development. Yet, despite the best intentions and efforts of many researchers and policy-makers, many of the indicators of development are still rather blunt instruments lacking in subtlety and resolution (Apthorpe, 1999; Midgley, 2003). Simply put, it is not easy to find or develop a metric or suite of metrics that flexibly measures the underlying well-being of a population. Micro-level data on individuals and households are much harder to collect than centralized, macro-economic indicators. The addition of even a single question to the censuses of multiple countries would require extraordinary resources and coordination. Such difficulties are perhaps nowhere more evident than in the field of migration research, where, as discussed above, the very definition of a migrant can vary greatly from one nation to another.

For these reasons, it is a compelling possibility that new sources of insight on human behavior and development processes can be found in the data automatically generated through the everyday use of common technologies. Mobile phones, and the data trails they leave behind, are rapidly becoming ubiquitous in developing countries, and can provide a useful source of data not just in migration research, but for many disciplines concerned with human behavior and the social aspects of development. We have emphasized how the data can be used to track mobility and migration, but similar methods could be used to trace the spread of new diseases, measure patterns of information diffusion, or analyze the impact of mobile-based financial services (Blumenstock, Eagle, & Fafchamps, 2011). Since the data have such high spatio-temporal resolution, with careful thought they can be reworked into a number of flexible and nuanced indicators. Moreover, given the similarity of the network infrastructure being deployed worldwide, it is likely that the resultant metrics could be consistently measured in multiple countries and contexts.

5.2 *Ethical concerns*

The data we utilize and the methods we advocate do not come without limitations, and some of these are quite severe. While we have mentioned a few such limitations in the text above, it is worth re-emphasizing several particularly salient issues. First and foremost are the concerns regarding privacy and confidentiality. Having a detailed repository of information on an individual, with a time-stamped history of visited locations, is a delicate matter in any context. In developing countries, where many individuals are economically vulnerable, legal institutions are often fragile, and certain political freedoms cannot be taken for granted, these concerns are particularly important.

If the benevolence of the researcher can be assumed, there are several precautions that can help ensure the privacy of the individuals under analysis, above and beyond the standard set of best practices involved in working with human subjects. Most notably, a preponderance of recent research indicates that simply stripping data of personal identifiers is not an effective method of protecting subjects' privacy (Lazer et al., 2009). Data anonymization is a difficult task that requires more than the removal of identifying information (Bayardo & Agrawal, 2005; Zang & Bolot, 2011), and raw data on subject behavior should be treated with the same care as more obviously sensitive data such as names, addresses, and phone numbers.

More problematic is the case when the intentions of the analyst are not transparent. This is particularly relevant as an increasing number of mobile operators require subscriber identity module cards to be registered with personal identification documents, and in instances where the subject may not grasp the full extent to which data may compromise his or her privacy. While a robust body of work examines the privacy concerns inherent to working with data of this nature (Barkhuus & Dey, 2003; cf. Palen & Dourish, 2003), there are no pragmatic recipes for how to deal with what is an inherently ethical dilemma. We have endeavored to demonstrate how these data can be used to improve development policy, but cannot reject the possibility that derivative methods would be used for less desirable purposes.

5.3 *Additional limitations*

In addition to these ethical considerations, there are several practical limitations of ICT-generated data. One such consideration that is particularly relevant in developing countries pertains to potential sampling bias and the external validity of the conclusions drawn from a non-representative sample of the population. As noted earlier, there are significant differences between Rwandans who own mobile phones and Rwandans who do not own mobile phones (Blumenstock & Eagle, 2012), and any inferences that are made on one population do not necessarily apply to the other. Patterns of technology adoption are, in general, not random (Rice & Katz, 2003), so while the external validity may increase as penetration reaches 100%, great care must be taken in generalizing results based on patterns of early adopters.

More insidiously, it is important to remember that in the analysis we conduct in this paper, we observe only the activity of the phone, and not of the owner. Thus, if the owner opts not to use his phone when he visits certain areas, even the most astute quantitative researcher will not know that the subject visited those locales. This incongruity between device and owner may also produce more subtle biases. For instance, many of the basic mobility statistics computed above have the tendency to over-report the mobility of individuals who are frequently active on the phone or who use the phone in urban areas. More sophisticated metrics can minimize these biases, but may be still be confounded by unmodeled factors.

A final, and rather mundane, problem with ICT-generated data is that it can be quite difficult to obtain the data in the first place. The mobile operators who store these data are often wary of releasing information that can be perceived to pose a threat to other business interests. It is our hope that, as mobile operators are exposed to the insights that can be realized from a judicious analysis of their data, they will grow increasingly amenable to using their data for research purposes. However, in the still nascent state of the field, this challenge will remain a major impediment to effective research for the foreseeable future.

6. Conclusion

In this study, we described the challenge of measuring internal migration in developing countries, and suggested that one potential solution may be found in the data generated through the everyday use of new ICTs. Using mobile phone data from Rwanda, we then showed how such data can be used not only to compute the aggregate levels of migration captured in a typical government survey, but also to measure more subtle patterns of mobility.

After formally developing a measure of *inferred migration*, our empirical analysis reveals very high levels of temporary and circular migration in Rwanda, a finding that is consistent with the qualitative literature but, to our knowledge, one that has not been previously documented with quantitative techniques. Finally, using a rich set of metrics on mobility and migration, we document how different types of individuals exhibit very different patterns of movement. It is our hope that the results presented in this study can provide a new perspective on internal migration and human mobility in developing countries, and that further refinement of these methods can provide insight into patterns of migration that otherwise are difficult to measure. More broadly, we believe that as mobile phones continue to proliferate in developing countries, and as data sets of this nature become more readily available, methods similar to those presented in this paper can be used to track and study a much wider range of phenomena of fundamental interest to those concerned with processes of human development.

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Notes

1. We focus our attention primarily on the effect of internal migration. For surveys of the much larger literature on the labor market effects of international migration, see Friedberg and Hunt (1995) and Borjas (1999).
2. A vibrant literature is being developed to describe the ways in which ICTs can have a positive impact on the lives of people and their communities, and on their social development (Aker, 2008; Jensen, 2007; Qureshi, 2009). While this paper is intimately related to that literature, the goal is different. Our intent, rather, is to emphasize how ICTs can help researchers and policy-makers better measure and evaluate processes of development, rather than assess the causal impact of the interventions themselves (be they ICT-based or not).
3. Bilsborrow (1997) provides an excellent overview of the strengths and weaknesses of the different sources of migration data.
4. A very closely related body of research addresses the ways in which ICTs can be used to better understand other aspects of human behavior beyond mobility and migration, including the structure of friendship networks (Onnela et al., 2007), the spread of innovations and products (Szabo & Barabási 2006), and patterns of economic growth (Eagle, Macy, & Claxton, 2010). See Kwok (2009) and Hazas Scott, and Krumm (2004) for brief overviews of this literature.
5. http://www.itu.int/ITU-D/ict/statistics/at_glance/KeyTelecom.html, Accessed July 2011. It should be noted, however, that mobile penetration in Africa is the lowest worldwide at 41%, and that in certain countries the uptake is much lower.
6. During the window of time we examine, the operator we focus on maintained over 90% market share of the mobile market. The company's primary competitor did not gain traction in the market until the end of 2008, and only more recently has the market become competitive. The number of landlines in Rwanda is insignificant (roughly 0.25% penetration).
7. All notation remains as before, except that we allow for *i*'s ROG and COG to vary by month (i.e. ROG_i is *i*'s total ROG, whereas ROG_{ik} is *i*'s *ROG* during the month *k*).
8. In an effort to make our statistics more comparable with those collected by the Rwandan government, we count migrations that occurred during the 3-month period from December 2007 through February 2008, which is exactly one year before the 3-month window queried in the CFSVANS survey. Unfortunately we do not have data from December 2008 through February 2009.
9. Among the primary sample of 901 mobile subscribers that we use in most of our analysis, over half used their phone for the first time in 2008, so it is not possible to compute as rich a set of longitudinal metrics for this group of individuals.

10. The fact that the migration rate among this sample of long-term subscribers is lower than the rate reported in Table 1 among all subscribers is further evidence that mobile phone users (in this case, early adopters) are different (in this case, less likely to migrate) from the at-large population.
11. The statistics in Table 2 differ from those in Table 1 because they are computed on a different sample (people active over 4 years *vs*. people contacted in the phone survey), and because Table 2 includes migrations over the entire 4-year interval, whereas Table 1 enumerates migrations in the 3-month window prior to March 2008.
12. This finding, which contradicts much of the prior literature on the subject, presents a mystery that we cannot explain without further evidence. However, we suspect that it may result from the fact that men and women who own phones may be more similar than men and women who do not own phones.
13. More generally, we interpret the fact that the migration statistics are not perfectly correlated with the mobility statistics as a validation of the quantitative instruments we employ. For instance, we note that the overall (4-year) radius of gyration for people who do not migrate is not significantly different from that of those who do, which suggests that the definition of inferred migration proposed in (2a)–(2c) is not merely a by-product of the fact that people who move a lot (but do not migrate) are more likely to be inadvertently classified as movers.

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