Model 2: A graph-based model of segment borrowability

This report includes supplementary materials for:

    Operationalizing borrowability: A case study from phonological segments

In [1]:
```
import networkx as nx
import re

import pandas as pd
import numpy as np

from vincenty import vincenty
from scipy.spatial import Delaunay
```

In [2]:
```
import cartopy.crs as ccrs
import cartopy.feature as cfeature
from cartopy.io.img_tiles import Stamen

import matplotlib.pyplot as plt
from matplotlib.collections import LineCollection
```

In [3]:
```
def load_cldf_dataset(path_to_values, path_to_languages):
    values = pd.read_csv(path_to_values)
    languages = pd.read_csv(path_to_languages)
    return pd.merge(left = values, right = languages, how="left",
                    left_on="Language_ID", right_on="ID")
```

In [4]:
```python
from collections import Counter

def get_frequencies_w_inventory_collapsing(dataset):
    glottocode_to_inventory = defaultdict(set)
    for row in dataset.itertuples():
        if not pd.isnull(row.Language_ID):
            glottocode_to_inventory[row.Language_ID].add(row.Value)
    print(f'{len(glottocode_to_inventory)} languages')
    frequencies_absolute = Counter()
    for segments in glottocode_to_inventory.values():
        for segment in segments:
            frequencies_absolute[segment] += 1
    frequencies_relative = {
        segment: count / len(glottocode_to_inventory)
        for segment, count in frequencies_absolute.items()
    }
    return frequencies_absolute, frequencies_relative
```

In [5]:
```python
segbo = load_cldf_dataset('../data/segbo/cldf/values.csv',
                          '../data/segbo/cldf/languages.csv')
phoible = load_cldf_dataset('../data/phoible/cldf/values.csv',
                            '../data/phoible/cldf/languages.csv')
```

In [6]:
```python
phoible_languages = pd.read_csv('../data/phoible/cldf/languages.csv')

# Filter out languages without glottocodes and coordinates
not_na = lambda x: not pd.isna(x)
phoible_languages = phoible_languages.loc[
    phoible_languages['Glottocode'].map(not_na) &
    phoible_languages['Latitude'].map(not_na) &
    phoible_languages['Longitude'].map(not_na)
]
phoible_languages.index = phoible_languages['Glottocode']

phoible_languages_filtered = set(phoible_languages.Glottocode)
phoible = phoible.loc[ phoible.Glottocode.map(lambda gltc: gltc in phoible_languages_filtered) ]
```

In [7]:
```python
phoible_langs = set(phoible.Language_ID)
segbo = segbo.loc[ segbo.Language_ID.map(lambda gltc: gltc in phoible_langs) ]
```

Construct the graph

In [8]:
```
# http://earthpy.org/tag/scipy.html
def lat_lon_to_cartesian(lat, lon, R = 1):
    """
    calculates lon, lat coordinates of a point on a sphere with
    radius R
    """
    lon_r = np.radians(lon)
    lat_r = np.radians(lat)

    x = R * np.cos(lat_r) * np.cos(lon_r)
    y = R * np.cos(lat_r) * np.sin(lon_r)
    z = R * np.sin(lat_r)
    return (x,y,z)
```

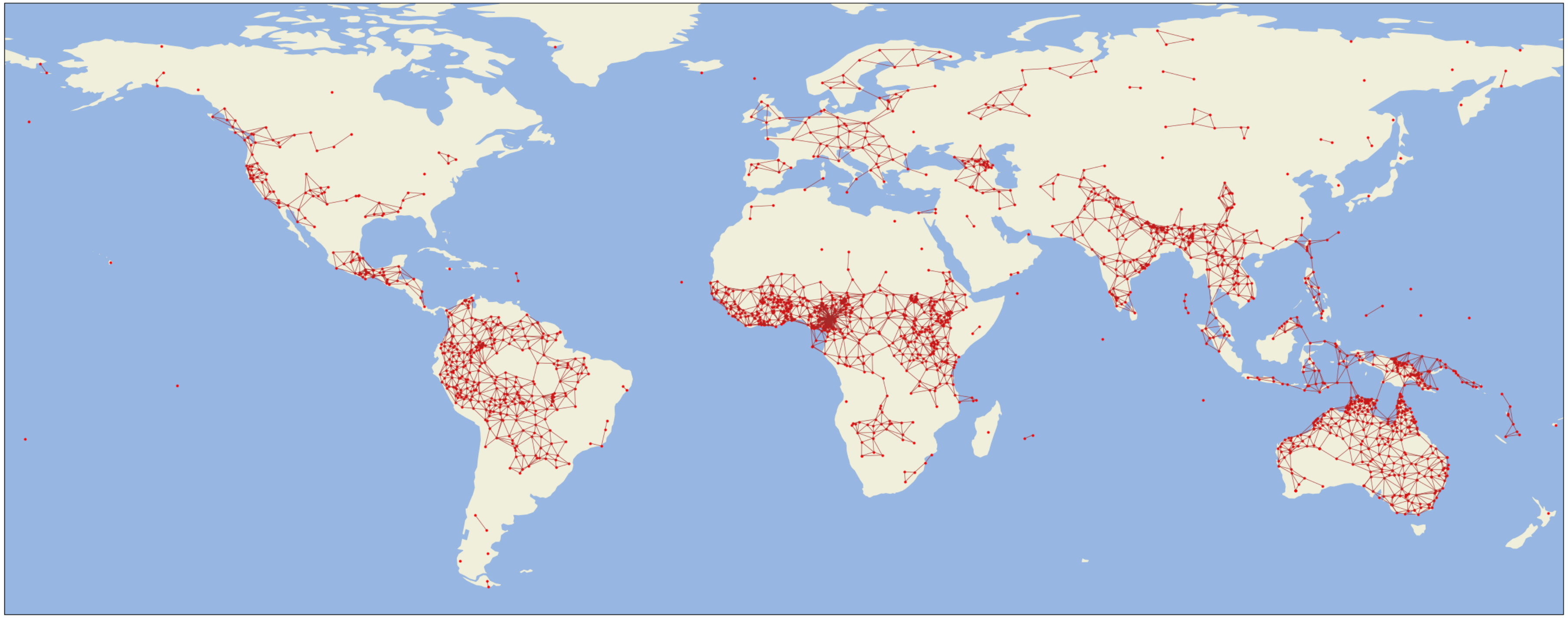
In [9]:
```python
def plot_graph(G_loc, coords_dict, figsize=(16,10)):
    # Create points
    lats = []
    lons = []
    for lang, coords_tuple in coords_dict.items():
        if lang in G_loc.nodes():
            lat, lon = coords_tuple
            lats.append(lat)
            lons.append(lon)

    fig = plt.figure(figsize=figsize)
    ax = plt.axes(projection=ccrs.PlateCarree())
    ax.add_feature(cfeature.LAND)
    ax.add_feature(cfeature.OCEAN)
    plt.plot(lons, lats, marker='o', color='red', markersize=2,
             transform=ccrs.PlateCarree(), linewidth=0)

    # Create a line collection from the graph
    rev_t = lambda tpl: (tpl[1], tpl[0])
    lines = [[] for i in range(len(G_loc.edges()))]
    for i, edge in enumerate(G_loc.edges()):
        t, h = edge
        lines[i] = [
            rev_t(coords_dict[t]),
            rev_t(coords_dict[h])
        ]
    lc = LineCollection(lines, colors='brown', linewidths=0.5)
    _ = ax.add_collection(lc)
```

In [10]:
```
coords_dict = {}
for row in phoible_languages.itertuples():
    coords_dict[row.Glottocode] = (row.Latitude, row.Longitude)

cartesian_coords_dict = {
    k: lat_lon_to_cartesian(*v) for k, v in coords_dict.items()
}

name_arr = sorted(coords_dict)
name_dict = {
    name: i for i, name in enumerate(name_arr)
}
points_arr = [cartesian_coords_dict[lang] for lang in name_arr]
```

In [11]:
```
tri = Delaunay(points_arr)
indptr, indices = tri.vertex_neighbor_vertices
```

In [12]:
```
G = nx.Graph()
for k in range(len(indptr)-1):
    point_gltc = name_arr[k]
    G.add_node(point_gltc)
    neighbours = indices[indptr[k]:indptr[k+1]]
    for n in neighbours:
        neigh_gltc = name_arr[n]
        if vincenty(
            coords_dict[point_gltc],
            coords_dict[neigh_gltc]
        ) <= 500:
            G.add_edge(point_gltc, neigh_gltc)
```

In [13]:
```
plot_graph(G, coords_dict, (32,20))
```



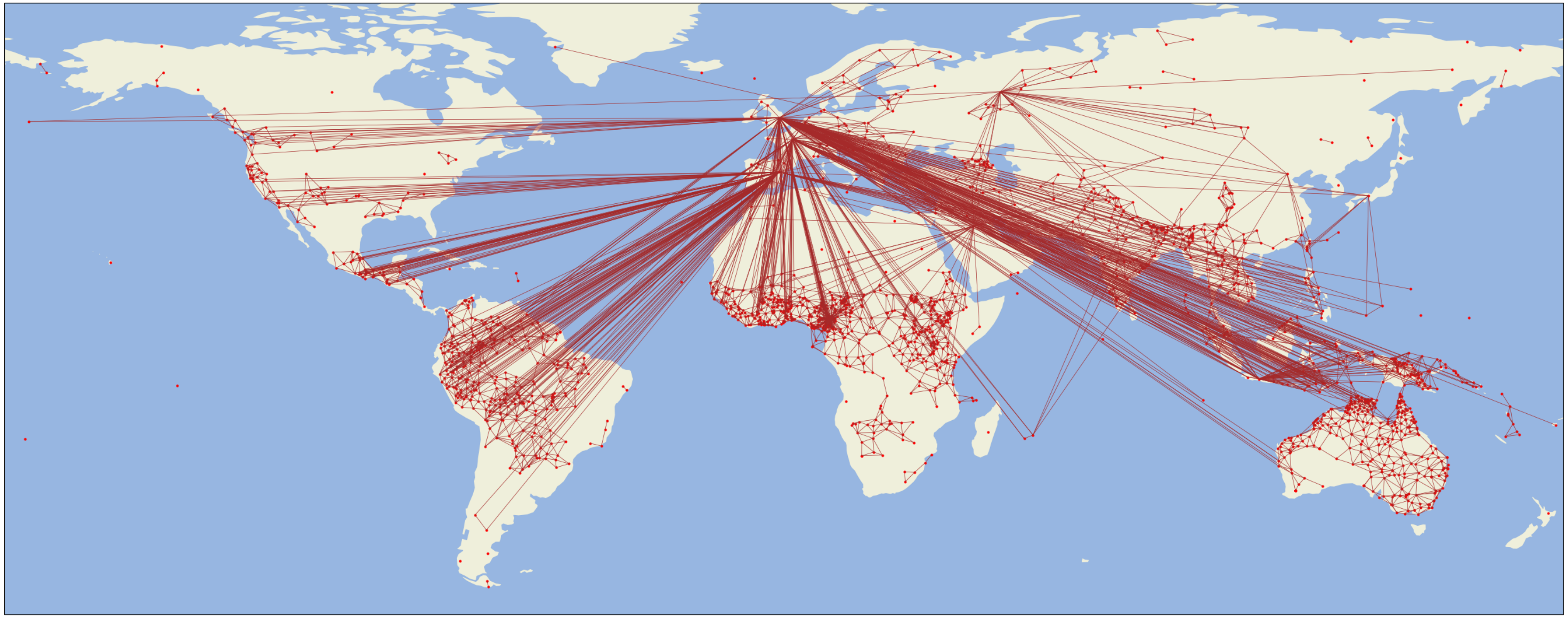
In [14]:
```
# Enrich the graph with new edges:
# connect with major languages all languages
# that borrowed segments from them together
# with their neighbours.
colonial = ['stan1288', 'stan1293', 'arab1395',
            'indo1316', 'russ1263', 'macr1272',
            'stan1290', 'dutc1256']
```

In [15]:

```
# The enrichment loop
for row in segbo.itertuples():
    gltc = row.Glottocode
    if gltc not in G.nodes():
        continue
    slgltcs_str = row.Source_Language_ID
    if pd.isna(slgltcs_str) or \
    slgltcs_str == 'unknown' or \
    slgltcs_str == '':
        continue
    slgltcs = re.split(r',\s*', slgltcs_str)
    for slgltc in slgltcs:
        if slgltc not in G.nodes():
            continue
        G.add_edge(gltc, slgltc)
        # For languages borrowing from colonial languages,
        # also connect their neighbours to the donour.
        if slgltc in colonial:
            try:
                for ngltc in G.neighbors(gltc):
                    G.add_edge(ngltc, slgltc)
            except KeyError:
                continue
```

In [16]:

```
plot_graph(G, coords_dict, (32,20))
```



The inference loop

For each language in the test set (langs without the segment in Phoible + langs that borrowed the segment), iterate over neighbours, look for contexts of exposure, count resulting borrowings.

In [17]:
```python
def report_borrowability(segment_, segbo_, phoible_, inventories_, borrowing_langs_, all_langs_, G_):
    '''
    Returns a tuple consisting of
    (test-set size, # exposed langs, # borrowing events, borrowability)
    '''
    if segment_ not in borrowing_langs_:
        raise IndexError(f'{segment_} is missing from the dataset.')
    # The test set consists of
    # (1) languages that don't have the segment
    no_seg = set(all_langs_) - set(
        phoible_.loc[phoible_.Value == segment_].Glottocode)
    # (2) languages that borrowed the segment
    test_set = no_seg.union(
        set(segbo_.loc[segbo_.Value == segment].Glottocode))
    test_set = set([el for el in test_set if G_.has_node(el)])

    exposure_count = 0
    borrowing_count = 0
    for gltc in test_set:
        for n in G_.neighbors(gltc):
            # We exclude languages that eventually borrowed the segment.
            if n in test_set:
                continue
            if segment_ in inventories_[n]:
                exposure_count += 1
                if gltc in borrowing_langs_[segment]:
                    borrowing_count += 1
                break
    return (
        len(test_set),
        exposure_count,
        borrowing_count,
        borrowing_count/exposure_count if exposure_count != 0 else 'NA'
    )
```

In [18]:
```python
all_langs = phoible.Glottocode.unique()
len(all_langs)
```

Out[18]:
```
2174
```

In [19]:
```python
# Put langs' inventories into sets for quick access
from collections import defaultdict

inventories = defaultdict(set)
for i, row in phoible.iterrows():
    inventories[row.Glottocode].add(row.Value)
```

In [20]:
```python
# Put langs that borrowed particular segments into sets
borrowing_langs = defaultdict(set)
for segment in segbo.Value.unique():
    for gltc in segbo.loc[
        segbo.Value == segment
    ].Glottocode.unique():
        borrowing_langs[segment].add(gltc)
```

In [21]:
```python
with open('borrowability_on_the_graph.csv', 'w', encoding='utf-8') as out:
    out.write('Phoneme,TestSetSize,ExpCount,BorrowingCount,Borrowability\n')
    for segment in borrowing_langs:
        out.write(
            segment +
            ',' +
            ','.join(str(el) for el in report_borrowability(
                segment, segbo, phoible, inventories, borrowing_langs, all_langs, G
            )) +
            '\n')
```

Compare the results of the graph-based model with those given by Model 1

In [22]:
```python
borrowability_dict = defaultdict(list)
for segment in borrowing_langs:
    _, _, _, b = report_borrowability(segment, segbo, phoible, inventories, borrowing_langs, all_langs, G)
    if b == 'NA':
        continue
    borrowability_dict['Segment'].append(segment)
    borrowability_dict['Borrowability'].append(b)
```

In [23]:
```python
model2 = pd.DataFrame(borrowability_dict)
```

In [24]:
```
model1 = pd.read_csv('../probablistic_model/model_1_borrowability.csv')
```

In [25]:
```
# Exclude rare segments
(
    segbo_frequencies_absolute,
    _
) = get_frequencies_w_inventory_collapsing(segbo)

model1 = model1.loc[
    model1.Segment.map(lambda x: segbo_frequencies_absolute.get(x, 0) >= 10)]
model2 = model2.loc[
    model2.Segment.map(lambda x: segbo_frequencies_absolute.get(x, 0) >= 10)]
```

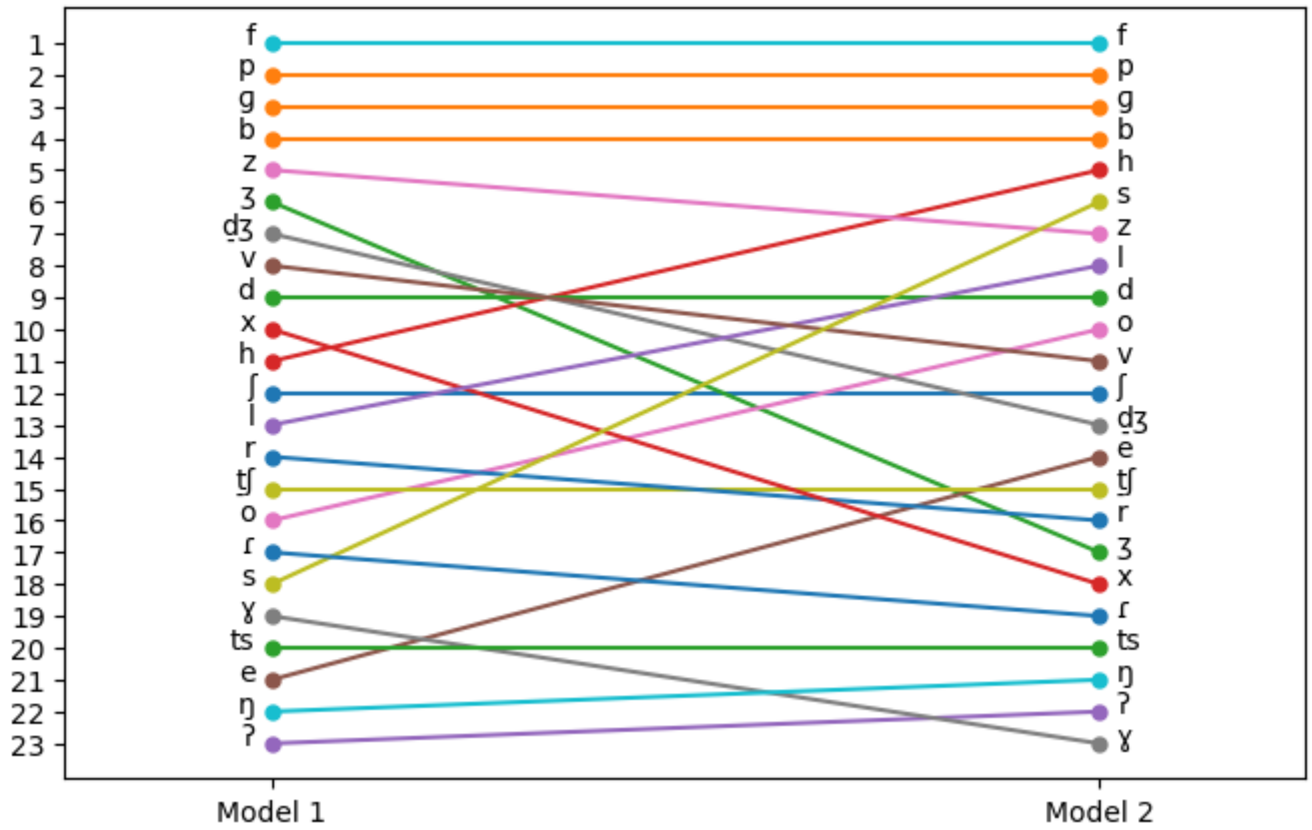
```
299 languages
```

In [26]:
```
# We convert scores to ranks for better comparability.
model1 = model1[['Segment', 'Borrowability']]
model1['Rank'] = model1.Borrowability.rank(ascending=False)
model2['Rank'] = model2.Borrowability.rank(ascending=False)
```

In [27]:
```
both_models = pd.concat([model1, model2])
both_models['Model'] = [0] * model1.shape[0] + [1] * model2.shape[0]
```

In [28]:
```
# Make sure that only segments covered by both models are included.
segments_for_analysis = set.intersection(set(model1.Segment), set(model2.Segment))
```

In [29]:
```
plt.figure(figsize=(8,5))
plt.gca().invert_yaxis()
for segment in segments_for_analysis:
    tmp = both_models.loc[both_models.Segment == segment]
    plt.plot(tmp.Model, tmp.Rank, marker='o', markersize=5)
    # end label
    plt.text(1.02, tmp.Rank.values[1], segment)
    # start label
    plt.text(-0.02, tmp.Rank.values[0], segment, ha='right')
_ = plt.xticks([0, 1], ['Model 1', 'Model 2'])
_ = plt.yticks(list(range(1, 24)))
plt.xlim(-0.25, 1.25)
plt.savefig('model_1_2_comparison_chart.pdf')
plt.show()
```



Model 1
Model 2
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